Climate trends and glacier retreat in the Cordillera Blanca, Peru, revisited

Schauwecker, Simone ; Rohrer, Mario ; Acuña, D ; Cochachin, Alejo ; Dávila, Luzmila R ; Frey, Holger ; Giráldez, Claudia ; Gómez, Jesús A ; Huggel, Christian ; Jacques-Coper, Martin ; Loarte, Edwin ; Salzmann, Nadine ; Vuille, Mathias

Abstract: The total glacial area of the Cordillera Blanca, Peru, has shrunk by more than 30% in the period of 1930 to the present with a marked glacier retreat also in the recent decades. The aim of this paper is to assess local air temperature and precipitation changes in the Cordillera Blanca and to discuss how these variables could have affected the observed glacier retreat between the 1980s and present. A unique data set from a large number of stations in the region of the Cordillera Blanca shows that after a strong air temperature rise of about 0.31 °C per decade between 1969 and 1998, a slowdown in the warming to about 0.13 °C per decade occurred for the 30 years from 1983 to 2012. Additionally, based on data from a long-term meteorological station, it was found that the freezing line altitude during precipitation days has probably not increased significantly in the last 30 years. We documented a cooling trend for maximum daily air temperatures and an increase in precipitation of about 60 mm/decade since the early 1980s. The strong increase in precipitation in the last 30 years probably did not balance the increase of temperature before the 1980s. It is suggested that recent changes in temperature and precipitation alone may not explain the glacial recession within the thirty years from the early 1980s to 2012. Glaciers in the Cordillera Blanca may be still reacting to the positive air temperature rise before 1980. Especially small and low-lying glaciers are characterised by a serious imbalance and may disappear in the near future.

DOI: https://doi.org/10.1016/j.gloplacha.2014.05.005

Originally published at:
Schauwecker, Simone; Rohrer, Mario; Acuña, D; Cochachin, Alejo; Dávila, Luzmila R; Frey, Holger; Giráldez, Claudia; Gómez, Jesús A; Huggel, Christian; Jacques-Coper, Martin; Loarte, Edwin; Salzmann, Nadine; Vuille, Mathias (2014). Climate trends and glacier retreat in the Cordillera Blanca, Peru, revisited. Global and Planetary Change, 119:85-97.
DOI: https://doi.org/10.1016/j.gloplacha.2014.05.005

Climate trends and glacier retreat in the Cordillera Blanca, Peru, revisited

S. Schauwecker[1,4], M. Rohrer[1], D. Acuña[2], A. Cochachin[3], L. Dávila[3], H. Frey[4], C. Giráldez[4], J. Gómez[5], C. Huggel[4], M. Jacques-Coper[6], E. Loarte[7], N. Salzmann[4,8], M. Vuille[9]

[1] Meteodat GmbH, Technoparkstr. 1, 8005 Zurich, Switzerland
[2] SENAMHI, av. Las Palmas s/n, Lima, Peru
[3] ANA, UGRH, Huaraz, Peru
[4] Department of Geography, University of Zurich, Winterthurerstr. 190, 8057 Zurich, Switzerland
[5] SERNANP, ANP Huascarán, Huaraz, Peru
[6] Institute of Geography, University of Berne, Hallerstr. 12, 3012 Berne, Switzerland
[7] Facultad de Ciencias del Ambiente, Universidad Santiago Antúnez de Mayolo, Huaraz, Peru
[8] Department of Geosciences, University of Fribourg, Chemin du Musée 4, 1700 Fribourg, Switzerland
[9] Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, 1400 Washington Ave., Albany, NY 12222, USA

Correspondence to: S. Schauwecker, schauwecker@meteodat.ch, +41 (0) 44 445 34 20

Abbreviations:

AAR	Accumulation Area Ratio
ANA	National Water Authority
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
CB	Cordillera Blanca
DJF, MAM, JJA, SON	Abbreviations for seasons
DTR	Daily Temperature Range
ECMWF	European Centre for Medium-Range Weather Forecasts
ELA	Equilibrium Line Altitude
ERA	Reanalysis at ECMWF
GDEM	Global Digital Elevation Map
GLIMS	Global Land and Ice Measurements from Space
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
PACC	Programa de Adaptación al Cambio Climático en el Perú
PDO	Pacific Decadal Oscillation
SENAMHI	National Meteorological and Hydrological Service of Peru
SEPA	Southeastern Pacific Anticyclone
SPOT	Satellite Pour l'Observation de la Terre
UGRH	Glaciology and Water Recources Unit
WGMS	World Glacier Monitoring Service

Abstract

The total glacial area of the Cordillera Blanca, Peru, has shrunk by more than 30% in the period of 1930 to the present with a marked glacier retreat also in the recent decades. The aim of this paper is to assess local air temperature and precipitation changes in the Cordillera Blanca and to discuss how these variables could have affected the observed glacier retreat between the 1980s and now. A unique data set from a large number of stations in the region of the Cordillera Blanca shows that after a strong air temperature rise of about 0.31°C per decade between 1969 and 1998, a slowdown in the warming to about 0.13°C per decade occurred for the 30 years from 1983 to 2012. Additionally, based on data from a long-term meteorological station, it was found that the freezing line altitude during precipitation days has probably not increased significantly in the last 30 years. We documented a cooling trend for maximum daily air temperatures and an increase in precipitation of about 60 mm/decade since the early 1980s. The strong increase in precipitation in the last 30 years probably did not balance the increase of temperature before the 1980s. It is suggested that recent changes in temperature and precipitation alone may not explain the glacial recession within the thirty years from the early 1980s to 2012. Glaciers in the Cordillera Blanca may be still reacting to the positive air temperature rise before 1980. Especially small and low-lying glaciers are characterized by a serious imbalance and may disappear in the near future.

Keywords: Cordillera Blanca; glacier change; climate change; equilibrium-line altitude (ELA); precipitation; air temperature

1 Introduction

The tropical Andes - and especially the Cordillera Blanca (CB) - have been recognized as a region highly vulnerable to climate change and the related glacier recession (e.g. Bury et al. 2010; Mark et al. 2010; Deutsch 2012). Glaciers in this region act as a temporal water storage for precipitation falling as snow at high elevations in the wet season from about October to April. The stored water is partly released during the dry season, compensating for the lack of water due to scarce precipitation events between May and September (Kaser et al., 2003). The discharge from the glaciated catchments is used in the downstream settlements particularly for mining, agriculture, domestic consumption and hydropower (Vuille et al., 2008a). The disappearance of these natural reservoirs has a dominant impact on the water availability in the Rio Santa valley particularly during the dry season (Juen et al., 2007; Baraer et al., 2012). As outlined by Deutsch (2012), rural communities and poor urban neighbourhoods in the Santa watershed, which drains the western part of the CB, face a threat of losing access to clean water, adequate to meet their basic domestic and livelihood needs. It is therefore indispensable to understand the response of glaciers to a changing climate in order to develop and implement related adaptation measures.

This study focuses on climatic trends and related glacier changes in the CB in the Peruvian Andes. Glaciers in the tropical Andes have witnessed a strong retreat during the last decades (e.g. Kaser 1990; Hastenrath and Ames 1995; Kaser and Georges 1997; Georges 2004; Mark and Seltzer 2005; Silverio and Jaquet 2005; Raup et al. 2007; Vuille et al., 2008a; Rabatel et al. 2013; Salzmann et al. 2013). Small glaciers in the tropical Andes at low altitudes show a more pronounced retreat, as the current equilibrium line altitude (ELA) climbed up towards the upper reaches causing a reduction or even loss of the accumulation area (Rabatel et al., 2013).

Several studies focusing on climate trends in the tropical Andes and the CB have been published. Based on a large number of stations along the tropical Andes between 1°N and 23°S, Vuille and Bradley (2000) and later Vuille et al. (2008a) observed a significant warming of approximately 0.1°C per decade between 1939 and 2006. They included station data from the network maintained by SENAMHI, however, they did not analyse temperature and precipitation trends for the region of the CB specifically. For the area of the CB, Mark and Seltzer (2005) reported a temperature increase of 0.39°C per decade between 1951 and 1999 and 0.26°C per decade between 1962 and 1999. They used data from the SENAMHI network from 29 and 45 stations for temperature and precipitation respectively, until 1998. They used temperature data to compute a trend for two time periods (1951-1999 and 1962-1999) and did not consider 30-year running trends as in the present work.

Precipitation changes are more difficult to document than temperature trends because of missing station records (Rabatel et al., 2013). In southern Peru and the Bolivian Altiplano, precipitation has decreased in the period 1950 to 1994, while station data indicate a slight increase for northern Peru for the same period (Vuille et al., 2003). Since precipitation is characterized by a large spatial variability, no clear pattern of increasing or decreasing precipitation can be found on a regional scale for the tropical Andes (Vuille et al., 2003). The understanding of local trends in meteorological variables is crucial to examine the glacier retreat in the CB. Therefore, trends of precipitation and air temperature in the CB are identified based on an extensive and unique in-situ data base. It is assessed how these local trends differ from general trends along the tropical Andes as published in e.g. Vuille et al. (2003) or Rabatel et al. (2013). The results are related to existing studies about linear temperature change in the CB such as from e.g. Mark and Seltzer (2005) and it is assessed how running 30-year trends varied in time.

The main objectives of this study can be summarized as follows: (i) Assessing recent trends in precipitation and near-surface as well as 500 hPa air temperature in the CB based on extensive in-situ measurements and reanalysis data with a focus on differences to the general trends in the tropical Andes. Additionally, it is examined how the running 30-year linear trends have changed in time since the 1960s and meteorological variables are compared to the upper-air zonal wind component during the austral summer and the Pacific Decadal Oscillation (PDO). (ii) Applying a novel approach to assess the increase in the freezing line altitude during precipitation days and to estimate the amount of precipitation needed to balance such an increase. (iii) Analysing the relation of precipitation and air temperature trends to observed glacier change using available mass balance measurements.

2 Study area

The CB is located between approximately 8°S and 10°S in the Ancash Region of Peru (Figure 1), spanning roughly 180 km in length and 20 km in width. The highest peak in this mountain range is the southern summit of the glaciated Nevado Huascarán with an elevation of 6768 masl. The lowest glacier extent is reached by Jatunraju glacier, whose debris-covered tongue ends at approximately 4200 masl. Although the distance to the Pacific Ocean is only about 100 km and more than 4000 km to the Atlantic, this range marks the continental divide. The Río Santa drains the western part of the CB, flows to the northwest into the Pacific and separates the CB from the Cordillera Negra in the west, which reaches altitudes of about 5200 masl. The western foothills of the Cordillera Negra descend to the Pacific coast.

The study site lies in the outer tropical zone and exhibits a typical climate for this region with a pronounced seasonality mainly in precipitation, cloud cover and specific humidity. The pronounced dry season spans from May to September, while the wet season is dominant in austral summer (Kaser and Georges, 1997). About 70 to 80% of the total annual precipitation falls within the pronounced wet season (Kaser et al., 1990). The seasonal distribution of precipitation is caused by the onset and demise of the South American monsoon system (Garreaud et al., 2009). During the wet season, precipitation mainly results from easterly winds transporting moisture from the Amazon Basin (Garreaud et al., 2003). During the dry months, precipitation in the valley bottom is almost zero, as plotted in Figure 2a. Precipitation at high elevations in the CB is more abundant. In contrast to the strong differences in seasonal precipitation, the area is characterised by small seasonal temperature variability (Figure 2b). Air temperature shows stronger diurnal than seasonal variability. The diurnal variability is higher in the dry season due to the lower humidity and cloud cover.

The mountain range of the CB is the largest glacierized area in the tropics, containing about one quarter of all tropical glaciers (Kaser and Osmaston, 2002). Several studies about glacier retreat in the CB have been published and they show consistently that total glacier area diminished heavily since 1930, as compiled in Figure 3. For 2003, Racoviteanu et al. (2008) document an area of 596.6 km^2 ± 21 km^2, whereas in 1930 the glacierized area was still around 800 to 850 km^2 (Georges, 2004).

3 Data

3.1 Meteorological station data

Station data were provided by the National Meteorological and Hydrological Service of Peru (SENAMHI), which maintains a national network of climate stations. The network consists of over 100 stations in the Ancash and the surrounding regions of which several are located in the CB. Additional daily time series are available from a network of six stations maintained by the Glaciology and Water Resources Unit (UGRH) of the National Water Authority (ANA) in Huaraz. The latter time series are available only since early 2000, which is too short of a period to compute climatically meaningful trends. However, this set provides important and unique information about air temperature in the last decade at high altitudes of more than 4000 masl. Mean monthly precipitation data are used from the network of Electroperú S.A. to calculate vertical precipitation gradients.

The available variables are daily mean, minimum and maximum temperature and total daily precipitation. Some stations also provide other variables like dew point, relative humidity, air pressure, wind speed and direction. Due to the large uncertainty associated with the data, these variables have not been considered in the present study. The data are available through a data portal, originally developed in the framework of the Swiss-Peruvian initiative for Climate Change Adaptation in Cusco and Apurimac (Programa de Adaptación al Cambio Climático en el Perú, PACC) from the Swiss Agency for Development and Cooperation (SDC), as described in Schwarb et al. (2011). For the present study, the data portal has been modified and contains now also data of the CB.

Figure 1 shows the locations of the available stations and Table 1 provides the details. The three highlighted stations Recuay, Artesoncocha and Buena Vista in Figure 1 were used to reconstruct reference stations. For the trend analyses in this work, the area is separated into two zones: Coast and Cordillera. The coastal region is defined for elevations up to 400 masl. For the Cordillera Region, only stations with a high correlation to the final reference station are considered. The lowest station with temperature data is Huari (3025 masl) and the lowest with precipitation data is Pampa Libre (1960 masl).

3.2 Reanalysis data from NCEP/NCAR and ERA-Interim

Three of the most widely used reanalysis products are the ones from the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) and from the European Centre for Medium-Range Weather Forecasts (ECMWF), described briefly in Table 2. Here, air temperature of the 500 hPa pressure level is used to derive trends of air temperature over the tropical Andes. The pressure level at 500 hPa corresponds to an average elevation range of about 5865 masl. The aim is to depict significant seasonal trends in air temperature between 1979 and 2012 at high elevations and to embed the results from station data into a larger framework of temperature changes along the tropical Andes. Additionally, zonal wind data were used from both ERA-Interim and NCEP/NCAR at the 250 hPa level for a 2.5° x 2.5° grid box (7.5 to 10°S and 75° to 77.5°W).

3.3 Present and historical glacier data

There are several field measurements of mass balance and estimations of ELAs used here to discuss the current state of glaciers in the CB. (i) The Glaciology and Water Resources Unit (UGRH) conducts mass balance measurements on Artesonraju and Yanamarey glaciers. For the hydrological year 2011 to 2012, they derived an actual ELA of 4975 masl for Artesonraju, and 4915 masl for Yanamarey (Dávila, 2013). (ii) Gurgiser et al. (2013) published field measurements from Shallap glacier. They document an actual ELA of 4985 masl for the season 2006/07 with a specific mass balance of -0.32 m w.e. and an actual accumulation area ratio (AAR) of 0.70. For 2007/08, they observed an actual ELA of 4953 masl with a specific mass balance of 0.56 m w.e. and an actual AAR of 0.74. Consequently, mass balance is zero when the steady state AAR is approximately 0.72 with a steady state ELA of 4973 masl. (iii) Mass balance data from Yanamarey and Artesonraju glaciers for the period 2005 to 2010 were made available by the World Glacier Monitoring Service (WGMS) (Zemp et al., 2012). (iv) Rabatel et al. (2012) documented ELAs of Artesonraju for each year between 2000 and 2010.

4 Methods

4.1 Quality check and homogenisation of climate data for trend analyses

In order to characterize spatial patterns of running 30-year temperature and precipitation trends, we analysed a large data set from stations along the Ancash coast and the mountainous region of the CB. Some of the stations from SENAMHI are operating since the early 1960s, but due to political and economic reasons, observations have been frequently interrupted or even shut down at times. This is why most records have gaps of different duration and some do not operate all the way to the present. Other stations have been in operation for the past 10 to 20 years.

In addition to missing data, there are other limitations of which one should be aware. Common limitations are inhomogeneities which may result from changes in a station's geographic location, instruments, averaging techniques or observers. A reliable climatic trend analysis, however, requires long and homogeneous data series (e.g. Begert et al., 2005) and respective data treatment prior to trend analyses is needed. The main aim of a homogenization is to identify and adjust implausible patterns, erroneous values or breaks caused by non-climatic factors, in order to create datasets suitable for climate change analyses.

As a first step, the available data series were checked regarding implausible values. A comparison with neighbouring stations shows whether outliers or breaks are plausible or not. Values classified as evidently erroneous are then deleted from the data series. For a climate change analysis of a region, air temperature and precipitation data of a complete and homogeneous long-term reference station are needed. However, in the CB and the time period from about 1960 to 2012, there is no homogeneous and complete time series available which could be utilized directly as reference station. To overcome this limitation, ensembles/clusters of available station series are used to substitute for one a single reference station. This procedure is described in e.g. Schwarb et al. (2011) or Salzmann et al. (2013). We created temporally complete temperature time series for a reference station in every zone (Cordillera region, the Cordillera region above 4000 masl and the coast) using a number of data series available. The following steps describe the approach applied here, relying on data homogenization and correction, with the aim of deriving one reference station for every region with an enhanced data quality.

- Relatively long and homogeneous data series were selected, which are henceforth referred to as “base stations”: Laredo, Paramonga and Buena Vista for the coast; Recuay, Oyon and San Rafael for the Cordillera; Artesoncocha for the Cordillera zone above 4000 masl (See Figure 1).
- Next, the correlation between these base stations and each station in the zone was computed based on daily values for maximum and minimum air temperatures. Only stations with a high correlation (R^2>0.6) to the base station were used in these further steps. Additionally, the pairs of station data were inspected visually and the Craddock test (Craddock, 1979) was applied in order to find inhomogeneous patterns between pairs of stations.
- Then, linear regressions were calculated between the measured maximum and minimum air temperature of the base station and each of the selected stations from the former step. Every linear regression is defined by a slope *m* and an intersect *q*.
- These linear regressions were used to create a new a time series for maximum and minimum air temperature for each base station $T_{base,sim}$ as follows:

$$T_{base,sim} = \frac{1}{n}\sum_{i=1}^{n}(T_{i,meas} \cdot m_i + q_i) \qquad (1)$$

  with $T_{base,sim}$ being the simulated temperature of every base station, *n* the number of stations with a high correlation (R^2>0.6) to the base station, *m* and *q* defining the linear regression between the base station and the selected stations in the zone. Figure 5 shows the new substituted time series for the three base stations for the Cordillera region and the Cordillera region above 4000 masl.
- Finally, one reference station was selected for each zone. The final reference stations are Buena Vista for the coast and Recuay for the Cordillera region. These stations are highlighted in Figure 1. As described before, the linear regression between the reference station and every base station was computed on a daily basis. The time series of the final reference stations was derived using linear regression with the base stations as predictors, corresponding to the former steps and Equation 1.

In addition to creating a reference station of temperature data, a representative time series of precipitation for the Cordillera region was also derived based on the Recuay station with a cluster of 18 base stations (Figure 1) using a monthly time step. In contrast to the approach for air temperature, only gaps of missing precipitation data of base stations are filled:

$$P_{base,sim} = \begin{cases} \frac{1}{n}\sum_{i=1}^{n}(P_{i,meas} \cdot m_i + q_i) & P_{base,meas} = n.i. \\ P_{base,meas} & P_{base,meas} =\geq 0 \end{cases} \qquad (2)$$

with $P_{base,sim}$ being the simulated precipitation of every base station, n the number of stations with a high correlation (R^2>0.8) to the base station, m and q defining the linear regression between the base station and the selected stations in the zone.

Running 30-year trends of air temperature were computed for the reference stations applying linear regressions. Seasonal trends were computed for the standard 3-monthly means (DJF, MAM, JJA, SON). The commonly used Mann-Kendall trend test is applied with a significance level of 0.05 to assess the significance of trends.

The transition from snow to rain during precipitation events is closely related to air temperature. The precipitation partitioning is crucial for the glacier surface albedo and the net shortwave radiation budget. Therefore, it is important to know how air temperature changed during precipitation events. As a novel approach, we here computed the change in freezing level for precipitation days. The analysis was based on station data from Recuay - the only station that provides long-term daily air temperature and precipitation records. The freezing level height for precipitation days is computed by extrapolating air temperature from Recuay, using a constant temperature lapse rate. Additional precipitation and air temperature records for 10 years from two high-elevation stations (Yanamarey, 4698 masl and Querococha, 4087 masl) are used to derive a lapse rate of -0.80°C/100m (standard deviation: 0.11°C/100m) for precipitation days at all three stations. This lapse rate corresponds to the one suggested by Carey et al. (2012), based on stations between around 3000 and 5000 masl. The lapse rate represents a mean daily lapse rate for days with precipitation. On average, precipitation occurs during 5 hours (standard deviation: 3.2 hours) on precipitation days. The lapse rate is therefore rather high for a moist adiabatic lapse rate and may lead to an underestimation of the freezing line altitude. However, the gradient does not influence the relative change in time of the freezing line.

The CB is an orographic barrier between the humid Amazon basin and the extremely dry Peruvian coastal region (Kaser et al., 2003). Precipitation over the CB mainly results from an easterly advection of moist air masses from the Amazon Basin and locally induced convective cells (Kaser and Georges, 1997). In order to understand how precipitation is linked to the large-scale circulation, the role of zonal flow in the interannual variability of precipitation is documented. Therefore, austral summer (DJF) precipitation is compared to the upper-air zonal wind component at 250 hPa, used as an index for advection of moist air masses from the interior of the continent. The actual advection of humidity, however, does not occur at that level. These winds only serve to entrain easterly momentum through downward mixing – the actual moisture influx occurs through near surface level upslope flow.

Additionally, the annual precipitation and air temperature is compared to the Pacific Decadal Oscillation (PDO, Mantua and Hare, 2002). The PDO index is provided by National Oceanic and Atmospheric Administration (NOAA) web-site and compared to annual precipitation and temperature data at the reference station Recuay.

4.2 Glacier characteristics

Glacier characteristics and glacier-climate-interactions are discussed based mainly on two approaches. First, a simple experiment is conducted with the aim to estimate the amount of precipitation needed to balance an increase in the snowline altitude during precipitation events. Second, available mass balance measurements and ELA estimations on two glaciers are compiled and compared to the glacier hypsography, in order to discuss the glacier imbalance.

In the first approach, a simple numerical experiment is applied to Shallap glacier. The aim is to estimate the amount of precipitation needed to balance an observed rise in the snowline during precipitation events. The sensitivity of the glacier mass balance to albedo changes is estimated similar to Klok and Oerlemans (2004). The main assumption of this experiment is that the elevation of the snowline has increased and the elevation band between the former and the current snowline has changed from snow-covered to bare ice. Due to the much lower albedo of a bare ice surface of the elevation band, the outgoing shortwave radiation is smaller and, consequently, more energy is available for ablation. The estimations are based on data from Gurgiser et al. (2013) and the glacier hypsography from the year 2003. Seasonal mean values of energy fluxes and surface are utilized, assuming that all fluxes (except for outgoing shortwave radiation) are constant and the fraction of sublimation to total ablation is 12.5% and 75% for the wet and dry season, respectively (Winkler et al., 2009).

For the second approach we used the glacier hypsography at different stages which delivers information on the area distribution across elevation. The hypsography measured at different points of time indicates the rate of area lost within different elevation bands. The hypsography is derived using glacier boundary outlines combined with an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Map (GDEM) at a resolution of 30 m (released in October 2011). Outlines from 2003, based on Satellite Pour l'Observation de la Terre (SPOT) images, are freely available through Global Land and Ice Measurements from Space (GLIMS) glacier database (Racoviteanu et al., 2008). The contemporary positions have been drawn visually based on the high-resolution SPOT images from 2011 and 2012, available through GoogleEarth.

The Accumulation Area Ratio (AAR) describes the ratio of the accumulation to the total glacier area. It is assumed that this ratio is constant for different glacier extents, given that the glacier is in equilibrium (Kerschner, 1990; Kaser and Osmaston, 2002b). Here, we distinguish between the actual AAR of an unbalanced glacier and the theoretical steady state AAR for a glacier in equilibrium. Different values for AAR in the CB are given in the literature: A steady state AAR of 0.82 is suggested by Kaser and Osmaston (2002) and Kaser and Georges (1997) estimated a steady state AAR of 0.75. The steady state ELA is here defined as the altitude of the equilibrium line, assuming a steady state AAR ranging from 0.75 to 0.82. Under certain conditions, a mean ELA of a stationary glacier can be determined by the application of an AAR to the hypsographic curve (Kerschner, 1990). This hypothetical steady state ELA corresponds to glacier mass conservation. The steady state ELA is compared to estimations of actual ELAs derived by mass balance measurements in the field. If the steady state ELA lies below the actual ELA, the glacier is unbalanced and it is assumed that the glacier will retreat until the theoretical and the actual ELA coincide.

5 Results

5.1 Temperature and precipitation changes

Temperature changes are analysed by calculating 30-year running mean changes for maximum and minimum air temperatures (Figure 4). Significant trends are highlighted in Figure 4 according to the Mann-Kendall test at the 0.05 level based on annual mean air temperature. Our results show that there is a notable difference between air temperature trends for the CB and the coast. In the Cordillera region, the running 30-year mean annual air temperature increase has slowed down during the recent decades from a maximum of significant 0.31°C/decade in the period 1969 to 1998 to significant 0.13°C/decade in the past thirty years from 1983 to 2012 (Figure 4a). In this period, the minimum temperature has increased significantly by almost 0.29°C/decade, while maximum temperature has cooled insignificantly by about -0.04°C/decade. Accordingly, the daily temperature range (DTR) has decreased over the period 1974 - 2003. In contrast to the decelerated but still increasing daily mean air temperatures in the Cordillera, a general cooling of air temperature at coastal stations is observed for the 30-year period of 1983 to 2012 of -0.22°C per decade (Figure 4c). The negative trend is found for minimum and maximum daily temperatures, however, only the maximum temperature is decreasing significantly. For stations above 4000 masl, air temperature was “stagnant” between 2002 and 2012 (Figure 5). The temperature decrease is not significant with a trend of -0.04°C for this decade. Figure 5 shows the annual times series of the four reference stations for the CB (San Rafael, Recuay, Oyon and Artesoncocha) and the final reference station Recuay.

Running 30-year air temperature trends for seasonal values were computed for both Cordillera and coastal stations between the 1960s and 2012. For air temperature in the CB, the highest increase was found for minimum temperatures during the dry season JJA and in the transition season SON

(Figure 4b). Also for the coastal stations, minimum air temperature is increasing for these two seasons JJA and SON (Figure 4d).

In order to compare the trends in the CB to the general trends of the tropical Andes, we computed seasonal trends of 500 hPa temperature for the period 1979 – 2012 based on reanalysis data. Figure 6 shows seasonal trends over the tropical Andes, based on ERA-Interim and NCEP/NCAR data. For both ERA-Interim and NCEP/NCAR the strongest warming is found for the season JJA over the Andes at around 20°S. The warming trends are strong and significant over the southern Andes in almost all seasons in both reanalysis products. In contrast, over the tropical Andes between approximately 10°N and 10°S (northern Peru, Ecuador, Colombia), temperatures tend to decrease. However, the cooling trends in the north are weak and less significant. The CB is located within the transition zone between the areas displaying a significant warming trend over southern Peru and Bolivia and the regions showing a slight cooling over northern Peru. Despite of the generally similar patterns of air temperature trends, there are large regional differences between ERA-Interim and NCEP/NCAR reanalysis data, particularly for the study site. ERA-Interim data show negative trends for all seasons for the cell of the CB, however the trend is not significant. In contrast to this, NCEP/NCAR reanalysis data show a warming for the grid cell of the CB. The 500 hPa temperature is increasing significantly by more than 0.2°C per decade for the austral winter and spring between 1979 and 2012.

Figure 7 illustrates the standardized mean annual air temperature from the reference station Recuay, the mean annual 500 hPa air temperature from NCEP/NCAR reanalysis and the average of mean annual 500 hPa air temperature from ERA-40 and ERA-Interim for the grid cell of the CB. NCEP/NCAR air temperature increases by 0.16°C per decade in the period from 1983 to 2012. In contrast, ERA-Interim temperature does not change significantly in the same period. The observed recent near-surface air temperature trends of about 0.13°C per decade are more consistent with NCEP/NCAR reanalysis data than ERA-Interim.

Figure 8 highlights that 1993 was characterised by a large annual precipitation total. After this event, mean decadal precipitation remained at a higher level than before 1993. The increase of precipitation for the reference station Recuay is about 60 mm/decade for the 30 years between 1983 and 2012. Figure 9 shows boxplots of decadal means of annual and seasonal precipitation for a set of eight stations in the CB in order to show the range of precipitation among different stations. Between the decade of the 1980s and 1990s, the increase in annual precipitation was more than 200 mm and is observed by all stations. The shift in precipitation affects annual values and all seasons, except for the dry season JJA where precipitation is decreasing. For the dry season, the decade 1993 to 2002 - including the wet year 1993 was even the driest decade of the entire observation period.

In Figure 10, the standardized zonal wind at 250 hPa and the standardized precipitation for the month DJF exhibit a clear negative relationship between 1980 and 2012. Stronger (lower) easterly winds are related to wetter (drier) rainy seasons. A shift is identified toward larger precipitation and a stronger easterly wind component after 1993. Hence, this shift to larger precipitation may be influenced by a change in the upper tropospheric wind patterns. The correlation between the seasonal precipitation and seasonal zonal wind is relatively low with coefficients of determination of R^2=0.23 and R^2=0.28, for reanalysis data from NCEP/NCAR and ERA-Interim, respectively.

Annual precipitation at the reference station Recuay is not correlated with the Pacific Decadal Oscillation (PDO), with R^2=0.05. The correlation between the PDO and mean annual air temperature is approximately 0.5 for the 30-year period between the 1960s and 1990s. Then the correlation decreases and is below 0.1 for the 30-year period from the late 1970s to the late 2000s.

An increase in the freezing line altitude during precipitation days of about 160 m is observed between the two decades 1964/72 and 1983/92 based on meteorological data from Recuay station (Figure 11). In contrast to this strong increase, the height of the freezing level for precipitation days has not changed significantly in the last 2 decades.

5.2 Glaciers states

Figure 12 shows the hypsography for 2003 and 2011 of two glacier with mass balance measurements available: a relatively small, low elevation glacier (Yanamarey) and a relatively large glacier with elevations extending up to about 5900 masl (Artesonraju). There is a distinct areal retreat of Yanamarey characterized by areal losses on the front, but also on the lateral edges until the upper reaches of the glacier. The percent of area lost is much lower for Artesonraju glacier, where areal retreat is observed essentially along the tongue. Vertical lines indicate measured ELAs since 2000 for Artesonraju and 2005 for Yanamarey (Rabatel et al., 2012; Zemp et al., 2012; Dávila, 2013). Grey horizontal bars indicate the approximate range of Ablation Area Ratio (AAR), assuming steady state. For Yanamarey, all measured ELAs are above the range of the theoretical steady state ELAs, with the measured ablation area between about 50% to 70%. For Artesonraju, the measured ELAs lie mostly within the range of steady state ELAs. With one exception (2009/10 from WGMS), all measured AAR exceed 70%.

6 Discussion

6.1 Climatic trend

Temperature records from numerous stations in the CB show a reduced warming in the last 30 years as compared to earlier decades. The trends computed for the 30-year period before 1999 are consistent with the results by Mark and Seltzer (2005). They observed a slightly reduced warming for 29 stations in the CB in an analysis of temperature trends in the period 1962 to 1999 as compared to the earlier period 1951 to 1999, which agrees with the reduced warming until 2012 observed here. Despite of the reduced warming trends, the temperature is still increasing at a rate of approximately 0.13°C per decade during the last three decades.

In contrast to the reduced warming observed in the CB, an actual cooling was observed in the last 30 years for coastal stations of the Ancash region. This is consistent with results from Falvey and Garreaud (2009) and Jacques (2009) who similarly observed a decreasing air temperature trend after the 1970s along the west coast of Chile and southern Peru, respectively. These studies linked the cooling along the west coast of South America with the intensification of the Southeast Pacific Anticyclone (SEPA), and thus an enhancement of the Humboldt Current System, after the abrupt weakening of this system in mid 1970s. This previous SEPA weakening seems to have played a major role in the climate shift registered as sudden warming in sea surface temperature in the Southeastern Pacific and in surface air temperature in many stations across South America (Giese et al., 2002; Jacques-Coper, 2009).

The rise in temperature in the CB is the result of daily minimum temperature increasing at a larger rate than the decreasing daily maximum, which is equivalent to a decrease in the daily temperature range (DTR). The decrease in DTR is apparent after 1974 (analysing 30-year periods) at both Cordillera and coastal stations and may indicate an increase in specific humidity or cloud cover, as corroborated by Vuille et al. (2003) who found a significant increase in relative humidity for the period 1950 to 1995 along the Andean range. Additionally, Salzmann et al. (2013) reported a significant increasing trend in specific humidity in the southern Peruvian Altiplano over the past 50 years based on reanalysis data from NCEP/NCAR. Further research would be needed to understand more in-depth the trends in humidity and cloud cover over the tropical Andes.

Our data based on meteorological stations show that mean annual precipitation has strongly increased between the 1980s and 1990s. The increase in precipitation has also been observed by Vuille et al. (2003) for northern Peru between 5°S and 11°S (1950 to 1994). However, for general precipitation changes in the tropical Andes no clear pattern emerges (e.g. Vuille et al., 2003; Rabatel et al., 2013). A decreasing trend is observed, for example, over the Vilcanota region in the period

1965-2009 (Salzmann et al., 2013) and for southern Peru in the period 1950-1994 (Vuille et al., 2003). Figure 10 indicates that the austral summer precipitation (about 40% of the total annual precipitation) is correlated with the zonal wind flow. The shift in strength of the zonal wind towards stronger easterly winds coincides with the increase of precipitation after 1993. With the increase of zonal easterly flow, advection of moist air from the Amazon basin is favoured. Consequently, the variability of zonal wind explains partly the inter-annual fluctuations of precipitation in the CB since around 1980. The mechanism between ENSO years and mass balance of glaciers in the CB has been discussed previously (Vuille et al., 2008b). Changes in the upper-tropospheric zonal flow are associated with ENSO-related tropical Pacific SST (Vuille et al., 2008b). This mechanism is inducing westerly (El Niño) or easterly (La Niña) wind anomalies with reduced (El Niño) or enhanced (La Niña) moisture flux from the east, producing anomalously dry or wet conditions, respectively. This teleconnection mechanism is spatially incoherent and affects the CB in most, but not all years. Inter-annual variability of the seasonal-mean zonal wind is more pronounced and relevant for the variance of summertime convection over the Altiplano (Garreaud and Aceituno, 2001).

Results show that annual precipitation in the CB has a low correlation with the PDO. The relatively high correlation between air temperature and PDO for the 30-year period before about 1995 indicates a teleconnection. However, in the recent two decades, this correlation was very low. The increase in temperature in the late 1970s is correlated with the shift in the PDO and consistent with the well-known 1976 climate regime shift (e.g. Giese et al., 2002). This circulation shift clearly affects the observed 30-year air temperature trends.

The freezing level height during days with precipitation is estimated based on station data from Recuay at 3444 masl. An increase in the freezing level height of about 130 m is found between the two decades 1964/72 and 1973/82, but no significant increase in the freezing line occurred after about 1983, which is at odds with many other studies that have noted a clear and significant increase of the 0°C-isotherm (e.g. Bradley et al., 2009 or Rabatel et al., 2013). Bradley et al. (2009) found that over the 30 years between about 1979 and 2009, freezing level heights across the Tropics have risen by about 45 m on average. More recently, Rabatel et al. (2013) calculated an increase of the freezing line of 28.9 m per decade over the CB for the period 1955-2011 based on NCEP/NCAR reanalysis data. However, our results cannot be directly compared to the findings by Bradley et al. (2009) or Rabatel et al. (2013), since we only considered days with precipitation and our analysis is based on an extrapolation of only one station (Recuay). More work on this topic may be warranted to analyze whether these discrepancies are due to a regional anomaly or problems with the Recuay data.

6.2 Glacier retreat

Despite the slowdown of the temperature rise and an increase in precipitation, glacier retreat has continued at a high rate over the last 30 years. Here, it is discussed how the observed trends of meteorological variables may affect the glacier mass balance through changes in accumulation or ablation processes. In a second step, the glacier imbalance is discussed and differences in glacier retreat between large and small glaciers are highlighted.

Both, precipitation and temperature changes may affect the accumulation process. The precipitation increase observed during the wet and transition seasons SON, DJF and MAM would lead to an increase of solid precipitation in the accumulation area and thus, a more positive (or less negative) annual mass balance if precipitation is falling as snow. Vuille et al. (2008b) e.g. found that on interannual timescales, precipitation variability appears to be the main driver for glacier mass balance fluctuations in the CB. On the other hand, increasing air temperatures during precipitation events lead to a rise of the snowline. However, the increase of air temperature in the last 30 years is particularly dominant in the relatively dry seasons JJA and SON (Figure 4), where precipitation events are rather scarce. Additionally, the freezing level height during precipitation days has probably not increased significantly since the early 80s, as shown by data from Recuay station.

The ablation process of a glacier is controlled by the energy balance at the glacier surface. Since incoming shortwave radiation is the dominant energy source all over the year (e.g. Sicart et al., 2008; Gurgiser et al., 2013), glacier melt in the tropics depends to a large degree on the surface albedo (Rabatel et al., 2013) and the sensitivity of glaciers to albedo changes is high. The glacier surface albedo is largely influenced by the state of aggregation of precipitation (and ice surface having a much lower albedo compared to a snow surface), and the transition of snow to rain is closely related to air temperature. From the 1960s to the 1980s, the freezing line altitude - and thus the snowline altitude - during precipitation events increased. Consequently, net radiation absorption was higher where the glacier was snow-free and more energy was available for melt. If we assume an albedo of 0.2 for ice and 0.75 for snow (taken from Gurgiser et al., 2013) under constant conditions, about 3.2 times more energy from net shortwave radiance is available for the ablation process of an ice surface. The height of the freezing line during precipitation events is therefore crucial for the ablation process.

Additionally, higher air temperatures may lead to an increased sensible heat flux, which also results in increased ablation. However, the sensible heat flux is generally small compared to the energy supplied by shortwave and longwave radiation (Wagnon et al., 1999; Sicart et al., 2010; Gurgiser et al., 2013). An unknown remains the role of humidity and cloud cover. The decreased daily temperature range may indicate higher humidity and cloud cover in the last decades (as observed e.g. by Salzmann et al., 2013 for the Cordillera Vilcanota). An increase in cloud cover would result in lowered incoming shortwave and increased incoming longwave radiation (Sicart et al., 2010). Specific humidity, on the other hand, is crucial in the process of latent heat fluxes, since it determines the fraction of sublimation. In the CB, sublimation consumes 60 to 90% of the total available energy during the dry season (Sicart et al., 2005; Winkler et al., 2009). Since sublimation of ice needs 8.5 times more energy than melt, a decrease in the fraction of sublimation may lead to drastically increased ablation rates. As an example, a decreasing fraction of sublimation from 75% to 50% on a clear sky day in July would theoretically almost double total ablation.

Our results show that precipitation has increased significantly between the 1980s and 2012, which would lead to a more positive (or less negative) mass balance if precipitation is falling as snow. Additionally, while the freezing line altitude during precipitation days increased before the 1980s it did probably not increase significantly during the past 30 years. Glaciers have continued retreating since the 1980s which may be a contradiction at first sight. In order to get additional insights, a simple numerical experiment, described in the section "Methods" is conducted based on energy flux data from Gurgiser et al. (2013). Based on the available data, the increase of precipitation over the accumulation area of Shallap glacier is estimated, which would be needed to balance the increase in ablation in the elevation band between the former and the current freezing line altitude due to a decrease of albedo. The needed increase in annual precipitation was found to be 240 mm and 530 mm for data from 2007/08 and 2006/07, respectively. The total observed increase in precipitation of about 140 mm between 1964 and 2012 for the reference station Recuay would thus not compensate the increase of the snowline before about 1980. At Cahuish station at an elevation of 4550 masl, annual precipitation is about 30% higher than at Recuay station at about 3400 masl. Assuming that the precipitation increase is proportional to the annual precipitation, the increase would be about 180 mm between 1964 and 2012 at an elevation of about 4500 masl and still not enough to balance the increased ablation due to the shift in the snowline. This example based on Shallap glacier is very simple and the sensitivity of glaciers to changes in temperature and precipitation depends on several factors. For example, glaciers with a large accumulation area are more sensitive to changes in precipitation and would benefit more from an increase (Klok and Oerlemans, 2004).

In a second step, we focus on the glacier hypsography and mass balance measurements, which allows comparing actual ELAs to theoretical steady state ELAs and discussing if glaciers are unbalanced. The decrease in glacier area (in percent of the total area) is particularly high for small, low-lying and isolated glaciers like Yanamarey and Pastoruri. A certain shift of the ELA (as a result of a combination of climatic parameters involved, Kaser, 1995) has a much stronger effect on the AAR of a small glacier than the one of a large glacier (Paul et al., 2007), which makes small glaciers more sensitive to climate change (e.g. Rabatel et al., 2013). In other words, a shift in the ELA would lead to a much higher percentage of area lost for small glaciers than for large ones, but the total area lost might be larger for large glaciers. We found that actual measured ELAs of Artesonraju - a relatively large glacier - mostly lie within the range of estimated steady state ELAs. Probably, the actual ELA is still above the steady state ELA, but the rate of area retreat compared to the total area is much lower than for small glaciers. On the other hand, the actual ELAs of the low-elevation and small Yanamarey glacier are high compared to the estimated range of theoretical steady state ELAs. These small, low lying glaciers are thus probably strongly unbalanced and are going to shrink further and at a high rate in the next decades even if temperature was stagnant. These findings are in line with a recent study that reports different retreat scenarios for small glaciers with maximum elevations below 5400 masl and large glaciers with maximum elevation above 5400 masl (Racoviteanu et al., 2008; Rabatel et al., 2013). Rabatel et al. (2013) also showed that the annual mass balance of large glaciers ranges between negative (-2 m w.e. per year) to positive mass balance. Also Gurgiser et al. (2013) observed a positive mass balance on Shallap glacier in 2007/08. In contrast to this, small glaciers experienced a permanently negative mass balance, indicating their strongly unbalanced condition.

Temperature and precipitation changes since the 1980s may probably not completely explain the strong glacier retreat during the past 30 years. Here, we suggest that the recent glacier retreat may still occur in response to the strong temperature rise of more than 0.3°C per decade before 1980, especially in the 1970s. To further discuss the response of glaciers in the CB to a changing climate in the last decades, it is necessary to estimate the response time, a measure for the time taken for a glacier to adjust the its geometry to a new climate regime. Until now, little is known about the response times of CB glaciers (Kaser and Georges, 1997). A simple method for determining the response time of glaciers was developed by Jóhanneson et al. (1989) and applied e.g. in Hoelzle et al. (2003), based on maximum ice thickness at the equilibrium line and annual ablation at the glacier tongue. Generally, glaciers with low ice thickness at the equilibrium line and large annual ablation at the glacier tongue have smaller response times to climate perturbations than large glaciers. Measurements and estimates of ice thickness and annual ablation rates exist for some glaciers in the CB (e.g. Artesonraju) and allow estimating a response time on the order of 10 to 40 years. Hence, the strong glacier retreat observed over the past three decades may include a signal of the temperature increase before the 1980s, depending on the glacier. The moderate temperature rise over the past 30 years may have induced additional forcing. However, the interpretation of glacier responses to climatic forcing is challenging, since some causal climatic fluctuations happen at time scales shorter than reaction times and, consequently, the observed response of a glacier can be a reaction to a large number of overlapping causes (Kaser and Osmaston, 2002). In order to discuss more in-depth the response of glaciers in the CB to changes in meteorological variables in the last three decades, a more detailed assessment of factors such as ice dynamics or response time of glaciers of different characteristics like size, slope or orientation would be needed.

7 Conclusions

Here we presented air temperature and precipitation trends since the 1960s based on reanalysis and station data of a relatively dense station network in the region of the CB. The main aim was to identify changes in temperature and precipitation patterns and to relate these changes to the glacier retreat during the last 30 years until 2012. We summarize as follows:

- Air temperature trends are characterized by large regional differences. A slowdown in temperature increase was identified for the CB, as was a cooling of air temperature for the coast. These findings are in line with recent studies. Climate warming may be spatially heterogeneous and temporally discontinuous. The increase may rather take the form of step changes where periods of strong warming alternate with “stagnant” periods.
- Reanalysis data were compared to in-situ air temperature data acquired from regional networks of climate stations. The present study underlines that global climate products (NCEP/NCAR and ERA-Interim reanalysis data) may have limitations to analyse regional trends in air temperature and need careful evaluation.
- Precipitation has increased in the CB with a clear shift observed in the early 1990s. The increase in wet season precipitation is correlated with the strengthening of the upper-tropospheric easterly zonal wind component. The shift in precipitation can probably not balance the negative mass balance caused by a strong increase in air temperature and the related change in freezing- and snowline, which is observed before approximately 1990.
- The observed decrease in the daily temperature range may indicate an increase in specific humidity or cloud cover. This finding is in line with recent studies, however, reliable station data are missing and the effect of increasing humidity and cloud cover remains a missing piece to fully understand the interactions between climate and glacier retreat in the CB. Detailed and long-term field measurements are needed to assess how humidity changes influence the radiation budget and turbulent latent heat fluxes.
- The freezing line altitude during precipitation days has increased by about 160 m between the 1960s and the 1980s, based on data of Recuay station. Our analysis does not show significant change after this period. The large increase before 1980 probably caused a significant shift in the ELA, since ablation is governed by net shortwave radiation via surface albedo.

- We suggest that the strong glacier shrinkage in the CB during the last 30 years may result from the strongly unbalanced glacier states in relation with changes in meteorological variables that occurred in large part before 1980. Especially small and low-elevation glaciers are extremely sensitive to climate change and may disappear in the near future.

If the already scarce water resources of the poor population of the Santa valley further diminish, water conflicts could exacerbate dramatically in the near future. Consequently, adaptation measures for CB's population should be planned, incorporating the knowledge of climate-glacier interactions in order to properly estimate possible advantages and changes but also disadvantages and risks of the respective options.

8 Acknowledgements

This research was developed in the framework of Proyecto Glaciares, a program financed by the Swiss Agency for Development and Cooperation SDC. We acknowledge also the use of data from the SENAMHI and the UGRH. NCEP/NCAR reanalysis data are provided by the NOAA/OAR/ESRL PSD Boulder, Colorado, USA. ERA-40 and ERA-interim data are obtained from the ECMWF. GLIMS data are provided by the National Snow and Ice Data Center and the ASTER DEM is obtained through the DAAC Global Data Explorer, a product of METI and NASA. We are grateful for the comments by an anonymous reviewer, which helped to substantially improve this paper.

9 References

ANA, 2010. Inventario Nacional de glaciares y lagunas. Huaraz.

Baraer, M., Mark, B., McKenzie, J., Condom, T., Bury, J., Huh, K.-I., Portocarrero, C., Gomez, J., Rathay, S., 2012. Glacier recession and water resources in Peru's Cordillera Blanca. J. Glaciol. 58, 134–150.

Begert, M., Schlegel, T., Kirchhofer, W., 2005. Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. Int. J. Climatol. 25, 65–80.

Bradley, R.S., Keimig, F.T., Diaz, H.F., Hardy, D.R., 2009. Recent changes in freezing level heights in the Tropics with implications for the deglacierization of high mountain regions. Geophys. Res. Lett. 36, L17701.

Bury, J.T., Mark, B.G., McKenzie, J.M., French, A., Baraer, M., Huh, K.I., Zapata Luyo, M.A., Gómez López, R.J., 2010. Glacier recession and human vulnerability in the Yanamarey watershed of the Cordillera Blanca, Peru. Clim. Change 105, 179–206.

Carey, M., Huggel, C., Bury, J., Portocarrero, C., Haeberli, W., 2012. An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru. Clim. Change 112, 733–767.

Craddock, J.M., 1979. Methods of comparing annual rainfall records for climatic purposes. Weather 34, 332–346.

Dávila, L., 2013. Memoria anual de glaciares - 2012. Huaraz.

Deutsch, B., 2012. Vulnerabilities, competition and rights in a context of climate change toward equitable water governance in Peru's Rio Santa Valley. Glob. Environ. Chang. 22, 364–373.

Falvey, M., Garreaud, R.D., 2009. Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979–2006). J. Geophys. Res. 114, D04102.

Garreaud, R., Vuille, M., Clement, A.C., 2003. The climate of the Altiplano: observed current conditions and mechanisms of past changes. Palaeogeogr. Palaeoclimatol. Palaeoecol. 194, 5–22.

Garreaud, R.D., Aceituno, P., 2001. Interannual Rainfall Variability over the South American Altiplano. J. Clim. 14, 2779–2789.

Garreaud, R.D., Vuille, M., Compagnucci, R., Marengo, J., 2009. Present-day South American climate. Palaeogeogr. Palaeoclimatol. Palaeoecol. 281, 180–195.

Georges, C., 2004. 20th-Century glacier fluctuations in the Tropical Cordillera Blanca, Peru. Arctic, Antarct. Alp. Res. 36, 100–107.

Giese, B.S., Urizar, S.C., Fuc, N.S., Fuckar, N.S., 2002. Southern Hemisphere Origins of the 1976 Climate Shift. Geophys. Res. Lett. 29, 1–4.

Gurgiser, W., Marzeion, B., Nicholson, L., Kaser, G., Ortner, M., 2013. Modeling energy and mass balance of Shallap Glacier, Peru. Cryosph. 7, 1787–1802.

Hastenrath, S., Ames, A., 1995. Recession of Yamanarey Glacier in Cordillera Blanca, Peru, during the 20th century. J. Glaciol. 41, 191–196.

Hoelzle, M., Haeberli, W., Dischl, M., Peschke, W., 2003. Secular glacier mass balances derived from cumulative glacier length changes. Glob. Planet. Change 36, 295–306.

Jacques-Coper, M., 2009. Characterization of the mid-1970's climatic jump in South America. Universidad de Chile, Santiago, 147 p. (in Spanish). <www.tesis.uchile.cl/tesis/uchile/2009/cf-jacques_mc/pdfAmont/cf-jacques_mc.pdf>.

Jóhanneson, T., Raymond, C., Waddington, E., 1989. A simple method for determining the response time of glaciers, in: Oerlemans, J. (Ed.), Glacier Fluctuations and Climatic Change. Kluwer Academic Publishing, Dordrecht, pp. 343–352.

Juen, I., Kaser, G., Georges, C., 2007. Modelling observed and future runoff from a glacierized tropical catchment (Cordillera Blanca, Perú). Glob. Planet. Change 59, 37–48.

Kaser, G., 1995. Some notes on the behaviour of tropical glaciers. Bull. Inst. Fr. études Andin. 24, 671–681.

Kaser, G., Ames, A., Zamora, M., 1990. Glacier fluctuations and climate in the Cordillera Blanca, Peru. Ann. Glaciol. 14, 136–140.

Kaser, G., Georges, C., 1997. Changes of the equilibrium-line altitude in the tropical Cordillera Blanca, Peru, 1930-50, and their spatial variations. Ann. Glaciol. 24, 344–349.

Kaser, G., Juen, I., Georges, C., Gómez, J., Tamayo, W., 2003. The impact of glaciers on the runoff and the reconstruction of mass balance history from hydrological data in the tropical Cordillera Blanca, Perú. J. Hydrol. 282, 130–144.

Kaser, G., Osmaston, H., 2002. Tropical Glaciers. Cambridge University Press.

Kerschner, H., 1990. Methoden der Schneegrenzbestimmung, in: Liedtke, H. (Ed.), Eiszeitforschung. Wissenschaftliche Buchgesellschaft, Darmstadt, pp. 299–311.

Klok, E.J., Oerlemans, J., 2004. Modelled climate sensitivity of the mass balance of Morteratschgletscher and its dependence on albedo parameterization. Int. J. Climatol. 24, 231–245.

Mantua, N.J., Hare, S.R., 2002. The Pacific Decadal Oscillation. J. Oceanogr. 58, 35–44.

Mark, B.G., Bury, J., McKenzie, J.M., French, A., Baraer, M., 2010. Climate Change and Tropical Andean Glacier Recession : Evaluating Hydrologic Changes and Livelihood Vulnerability in the Cordillera. Ann. Assoc. Am. Geogr. 100, 794–805.

Mark, B.G., Seltzer, G.O., 2005. Evaluation of recent glacier recession in the Cordillera Blanca, Peru (AD 1962 – 1999): spatial distribution of mass loss and climatic forcing. Quat. Sci. Rev. 24, 2265–2280.

Paul, F., Maisch, M., Rothenbühler, C., Hoelzle, M., Haeberli, W., 2007. Calculation and visualisation of future glacier extent in the Swiss Alps by means of hypsographic modelling. Glob. Planet. Change 55, 343–357.

Rabatel, A., Bermejo, A., Loarte, E., Soruco, A., Gomez, J., Leonardini, G., Vincent, C., Sicart, J.E., 2012. Can the snowline be used as an indicator of the equilibrium line and mass balance for glaciers in the outer tropics? J. Glaciol. 58, 1027–1036.

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J.L., Basantes, R., Vuille, M., Sicart, J.-E., Huggel, C., Scheel, M., Lejeune, Y., Arnaud, Y., Collet, M., Condom, T., Consoli, G., Favier, V., Jomelli, V., Galarraga, R., Ginot, P., Maisincho, L., Mendoza, J., Ménégoz, M., Ramirez, E., Ribstein, P., Suarez, W., Villacis, M., Wagnon, P., 2013. Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. Cryosph. 7, 81–102.

Racoviteanu, A.E., Arnaud, Y., Williams, M.W., Ordonez, J., 2008. Decadal changes in glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing. J. Glaciol. 54, 499–510.

Raup, B., Racoviteanu, A., Khalsa, S.J.S., Helm, C., Armstrong, R., Arnaud, Y., 2007. The GLIMS geospatial glacier database: A new tool for studying glacier change. Glob. Planet. Change 56, 101–110.

Salzmann, N., Huggel, C., Rohrer, M., Silverio, W., Mark, B.G., Burns, P., Portocarrero, C., 2013. Glacier changes and climate trends derived from multiple sources in the data scarce Cordillera Vilcanota region, southern Peruvian Andes. Cryosph. 7, 103–118.

Schwarb, M., Acuña, D., Konzelmann, T., Rohrer, M., Salzmann, N., Serpa Lopez, B., Silvestre, E., 2011. A data portal for regional climatic trend analysis in a Peruvian High Andes region. Adv. Sci. Res. 6, 219–226.

Sicart, J.E., Hock, R., Ribstein, P., Chazarin, J.P., 2010. Sky longwave radiation on tropical Andean glaciers : parameterization and sensitivity to atmospheric variables. J. Glaciol. 56, 854–860.

Sicart, J.E., Hock, R., Six, D., 2008. Glacier melt, air temperature, and energy balance in different climates: The Bolivian Tropics, the French Alps, and northern Sweden. J. Geophys. Res. 113, D24113. doi:10.1029/2008JD010406

Sicart, J.E., Wagnon, P., Ribstein, P., 2005. Atmospheric controls of the heat balance of Zongo Glacier (16°S, Bolivia). J. Geophys. Res. 110, D12106.

Silverio, W., Jaquet, J.M., 2005. Glacial cover mapping (1987–1996) of the Cordillera Blanca (Peru) using satellite imagery. Remote Sens. Environ. 95, 342 – 350.

Vuille, M., Bradley, R., Werner, M., Keimig, F., 2003. 20th century climate change in the Tropical Andes: Observations and model results. Clim. Change 59, 75–99.

Vuille, M., Bradley, R.S., 2000. Mean annual trends and their vertical structure in the tropical Andes. Geophys. Res. Lett. 27, 3885–3888.

Vuille, M., Francou, B., Wagnon, P., Juen, I., Kaser, G., Mark, B.G., Bradley, R.S., 2008a. Climate change and tropical Andean glaciers: Past, present and future. Earth Sci. Rev. 89, 79–96.

Vuille, M., Kaser, G., Juen, I., 2008b. Glacier mass balance variability in the Cordillera Blanca, Peru and its relationship with climate and the large-scale circulation. Glob. Planet. Change 62, 14–28.

Wagnon, P., Ribstein, P., Kaser, G., Berton, P., 1999. Energy balance and runoff seasonality of a Bolivian glacier. Glob. Planet. Change 22, 49–58.

Winkler, M., Juen, I., Mölg, T., Wagnon, P., Gómez, J., Kaser, G., 2009. Measured and modelled sublimation on the tropical Glaciar Artesonraju, Perú. Cryosph. 3, 21–30.

Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Gärtner-Roer, I. Nussbaumer, S.U., 2012. Fluctuations of Glaciers 2005-2010. ICSU (WDS)/ IUGG (IACS)/ UNEP/ UNESCO/ WMO, World Glacier Monit. Serv. Zurich, Switzerland. Based database version X, 336 pp.

Table 1: List of all stations used as “base stations” in the analysis with the respective zone, altitude, variables, measuring period and data gaps. Stations with a symbol * were selected as a basis for reference stations. A gap in annual precipitation appears here where precipitation data are missing for at least one day. A gap in annual temperature appears where more than 10% of the daily data are missing.

Table 2: Details of the three reanalysis products.

Figure 1: Map of the glaciers in the Cordillera Blanca and the location of the here considered meteorological stations measuring temperature (red triangle) and precipitation (blue circle). Stations used as reference stations are marked with yellow stars. Stations with labels were used as base stations, due to relatively long and complete time series.

Figure 2: Monthly precipitation and air temperature in the Cordillera Blanca. (a) Multi-annual monthly mean precipitation registered at Caraz in the valley bottom (grey) and near Laguna Parón at over 4000 masl (black) between 1953 and 1995. (b) Multi-annual monthly mean of daily maximum, minimum and mean temperature for the station Recuay at 3444 masl for the period 1980 to 2011.

Figure 3: Total glacier area and uncertainty ranges for glaciers in the Cordillera Blanca between 1930 and 2003, compiled based on Georges (2004), Silverio and Jaquet (2005), Racoviteanu et al. (2008) and ANA (2010).

Figure 4: Running 30-year air temperature trends between 1964 and 2012 for the reference station Recuay in the CB and between 1960 and 2012 for the reference station Buena Vista at the coast for (a) and (c) annual maximum, mean and minimum air temperature; (b) and (d) seasonal maximum and minimum temperature. Black crosses in (a) and (c) indicate significant 30-year trends at the 5% level (according to the Mann-Kendall test) based on annual data.

Figure 5: Mean annual air temperature for the base stations San Rafael, Recuay and Oyon, the reference station Recuay and the reference station Artesoncocha.

Figure 6: Trends in air temperature between 1979 and 2012 at the 500 hPa level from (a) ERA-Interim and (b) NCEP/NCAR reanalysis data for DJF, MAM, JJA and SON. Black crosses indicate statistically significant trends (according to the Mann-Kendall test at the 0.05 level). The grid representing the CB is marked with a black box.

Figure 7: Standardized annual values for 500 hPa air temperature from reanalysis data for the grid cell of Cordillera Blanca (ERA-40, ERA-Interim, NCEP/NCAR) and standardized annual values for air temperature at the final reference station Recuay at 3444 masl.

Figure 8: Annual precipitation for the reconstructed final reference station Recuay at 3444 masl. The decades are marked by black lines.

Figure 9: Boxplots of decadal mean of annual and seasonal precipitation. Each boxplot consists of a set of data measured by eight stations in the Cordillera Blanca (Andajes, Cajamarquilla, Ocros, Oyon, Paccho, Parquin, Picoy, Pira).

Figure 10: Standardized DJF precipitation for the reference station Recuay and standardized DJF zonal wind from NCEP/NCAR and ERA-Interim between 1980 and 2012 for the 250 hPa level. Horizontal lines indicate mean values for the two periods 1980-1992 and 1993-2012. Note that scale on left-side y-axis is reversed. Positive (negative) zonal wind means westerly (easterly) winds.

Figure 11: Boxplots of freezing level height for days with precipitation. Each boxplot consists of a set of daily values. The 0°-level height was extrapolated based on daily air temperature data from Recuay (original time series) for days with registered precipitation. The temperature lapse rate is assumed to be -0.8°C/100m.

Figure 12: Cumulative frequencies of glacier surface area for Yanamarey (left) and Artesonraju (right) glaciers for 2003 and 2011 as a function of elevation. An AAR of 0.72 to 0.85 is assumed and describes the ratio of accumulation area to total area of a glacier in equilibrium (grey horizontal bar). The AAR allows estimating a range of steady state ELAs, which are needed to conserve the glacier mass. The actual, measured ELAs are indicated by vertical bars (black: WGMS, blue: Rabatel et al., 2012) and include measurements since 2005 for Yanamarey and 2000 for Artesonraju.

Figure1

Click here to download high resolution image

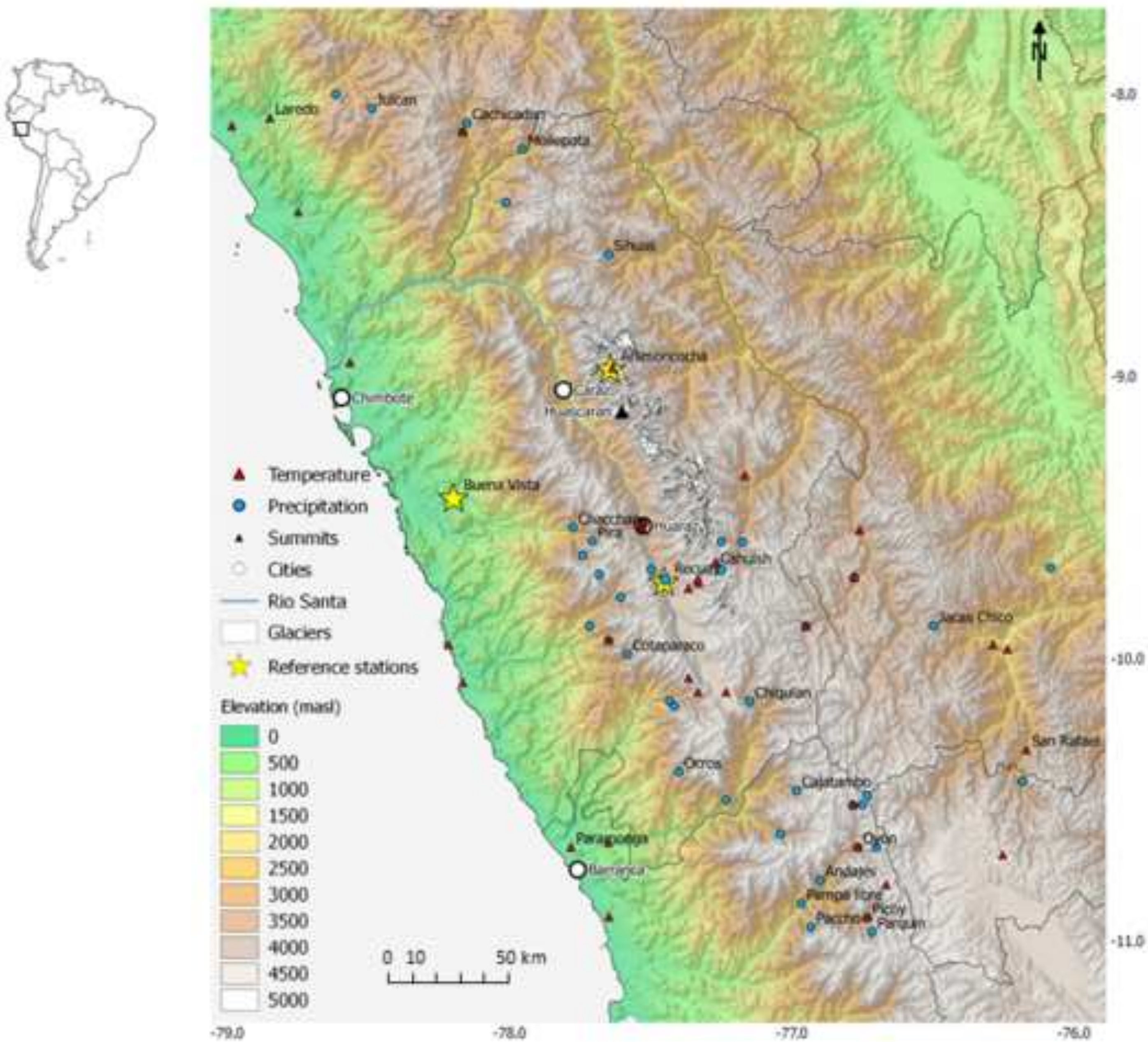

Figure2a
Click here to download high resolution image

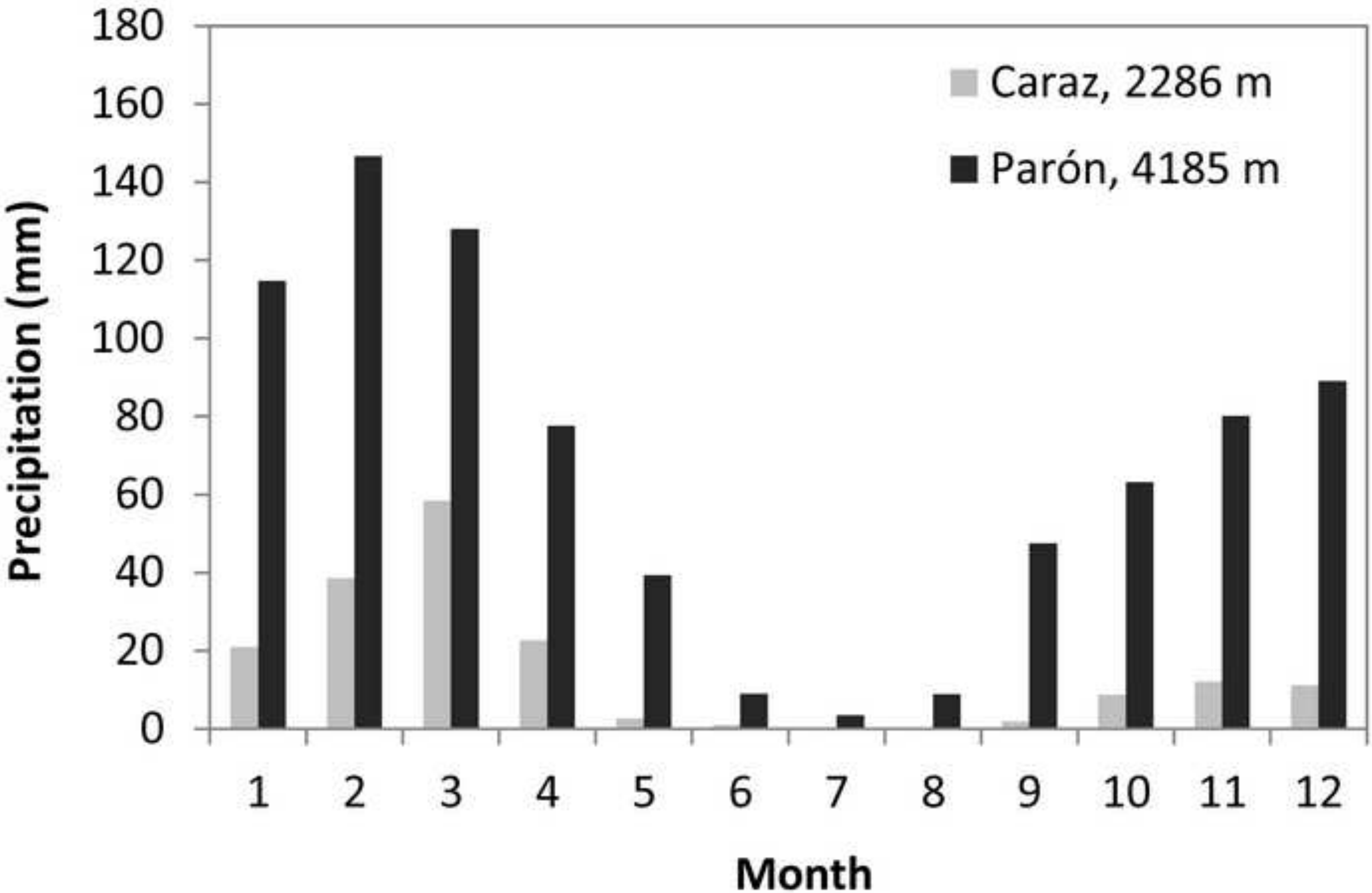

Figure2b
Click here to download high resolution image

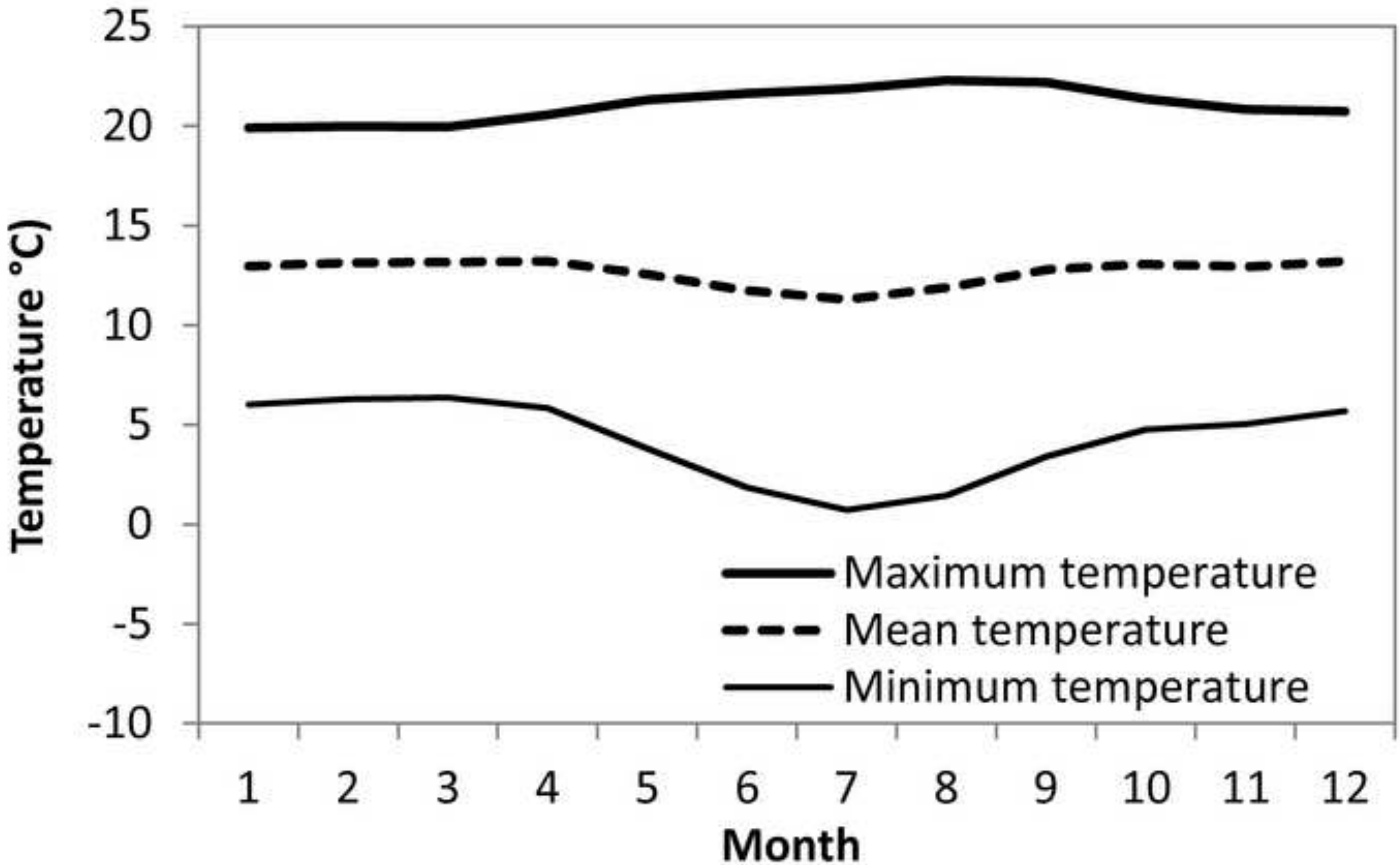

Figure3
Click here to download high resolution image

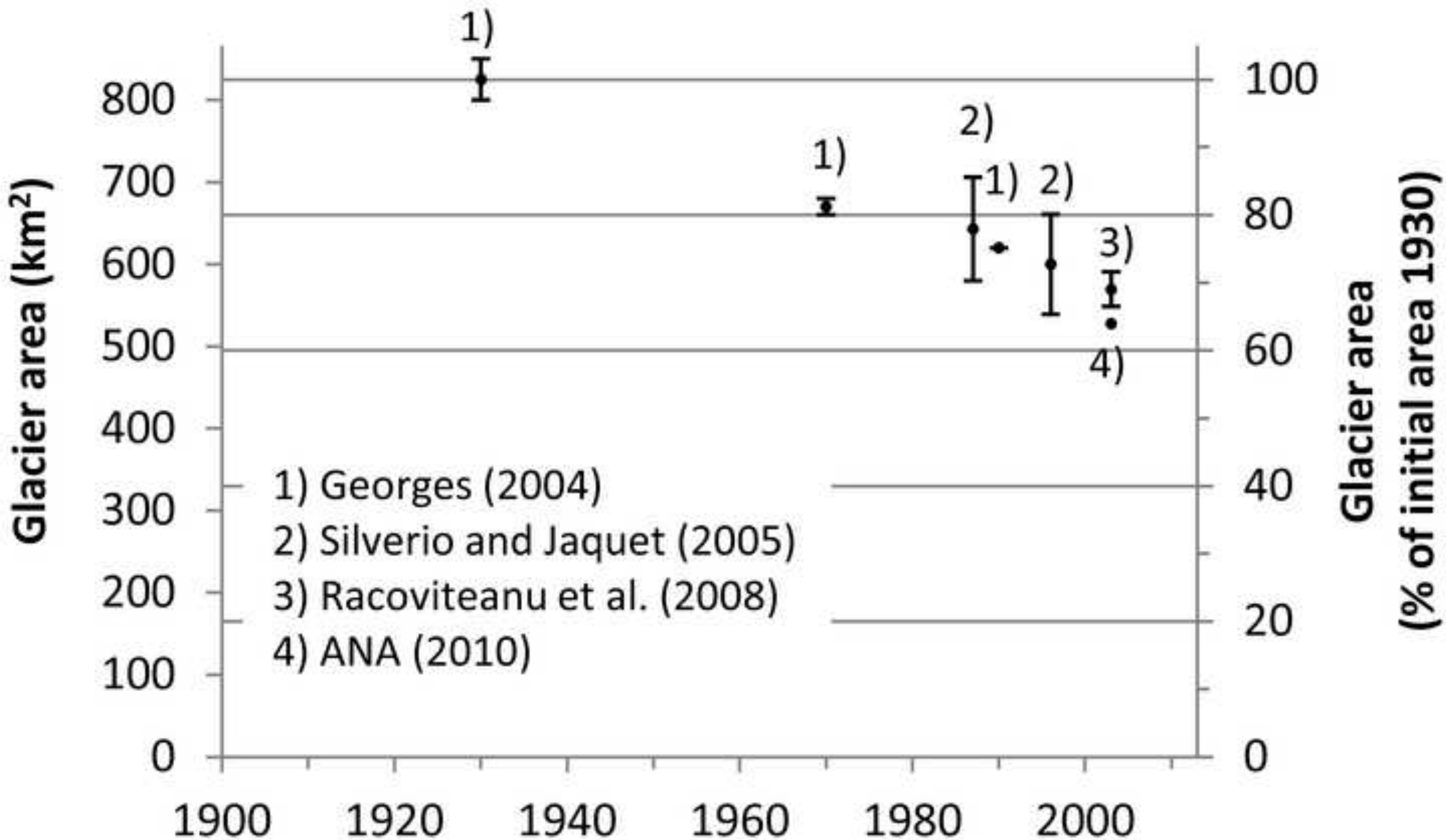

Figure4

Click here to download high resolution image

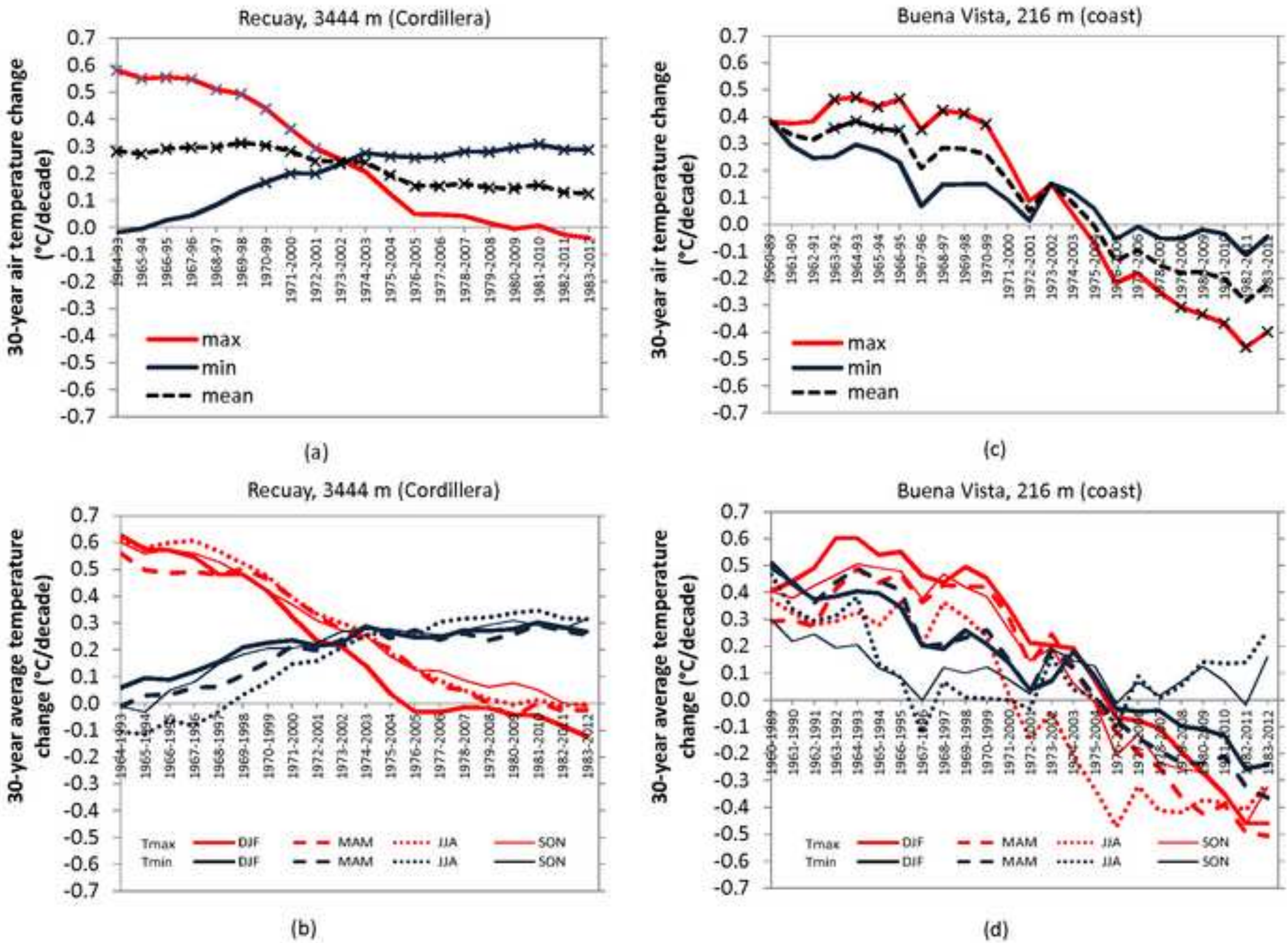

Figure5

Click here to download high resolution image

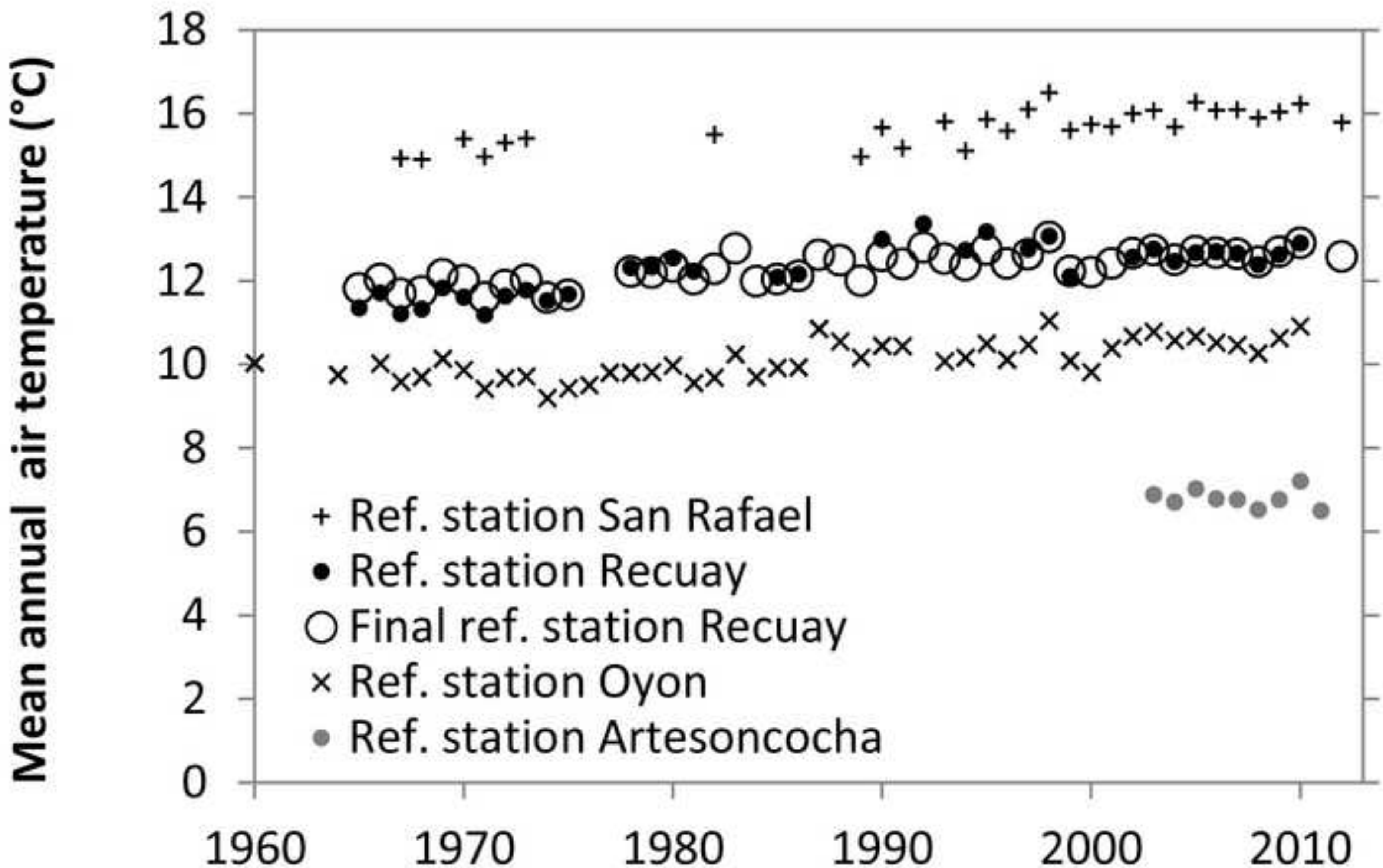

Figure6
Click here to download high resolution image

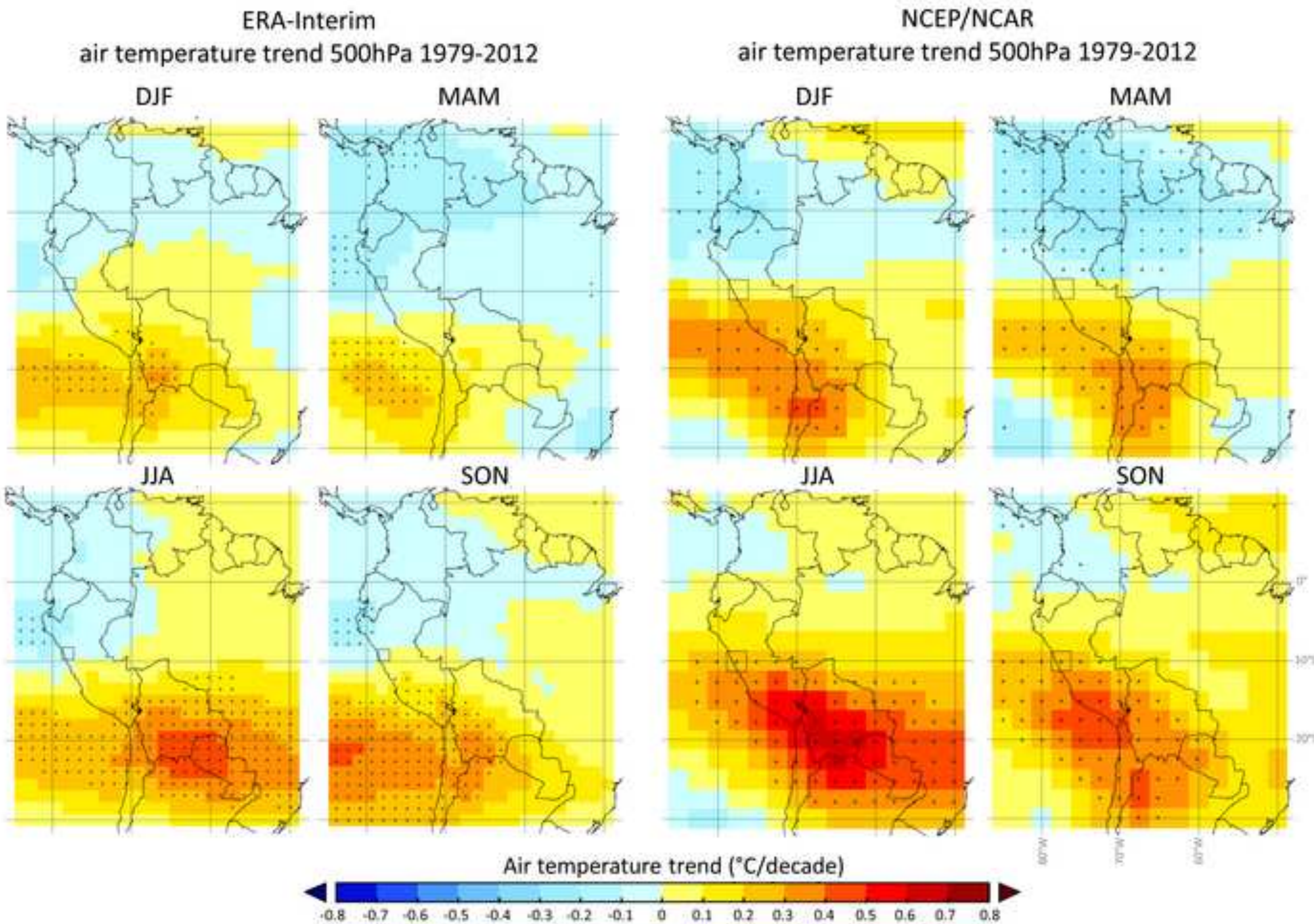

Figure7
Click here to download high resolution image

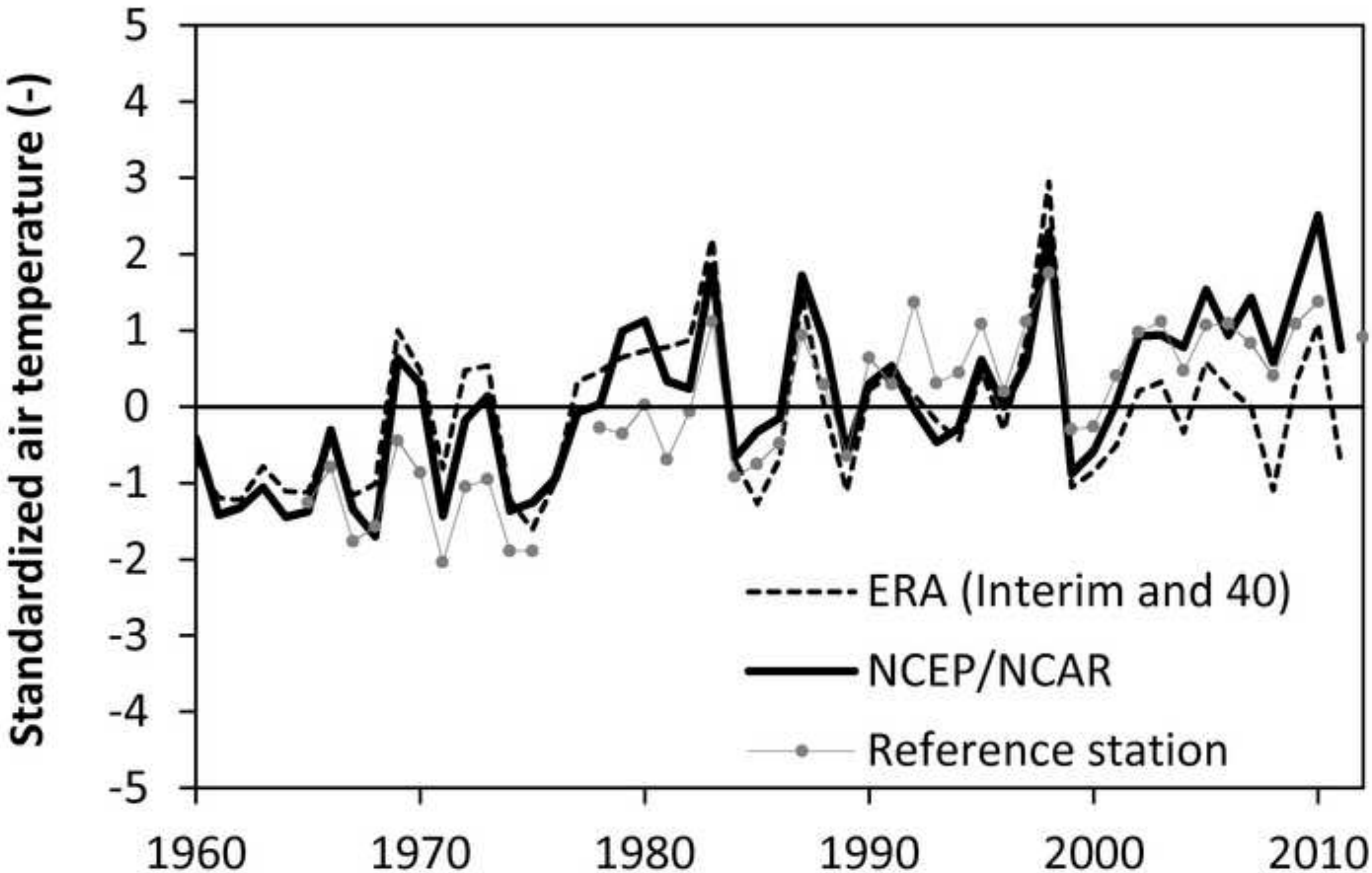

Figure8
Click here to download high resolution image

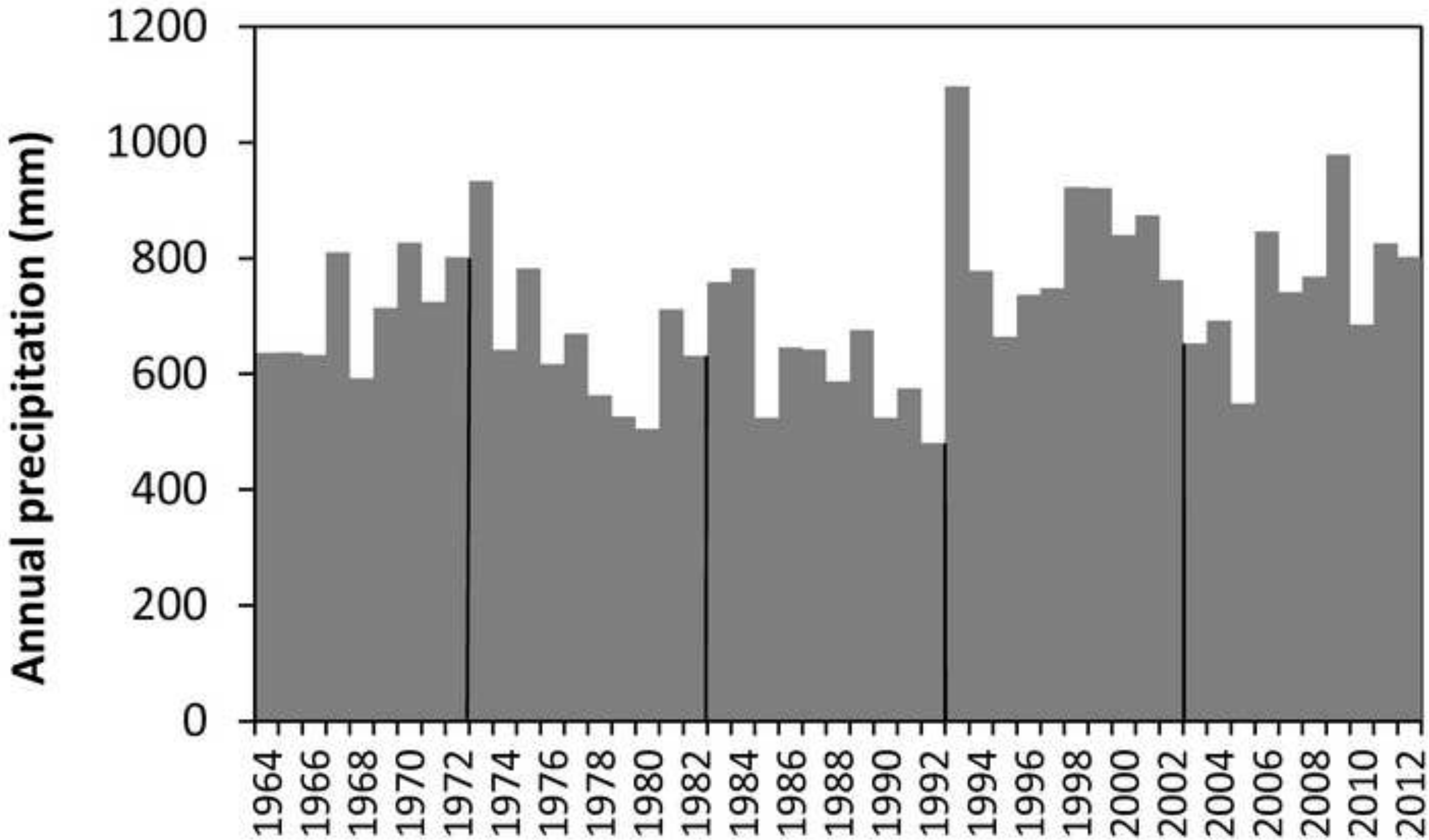

Figure9

Click here to download high resolution image

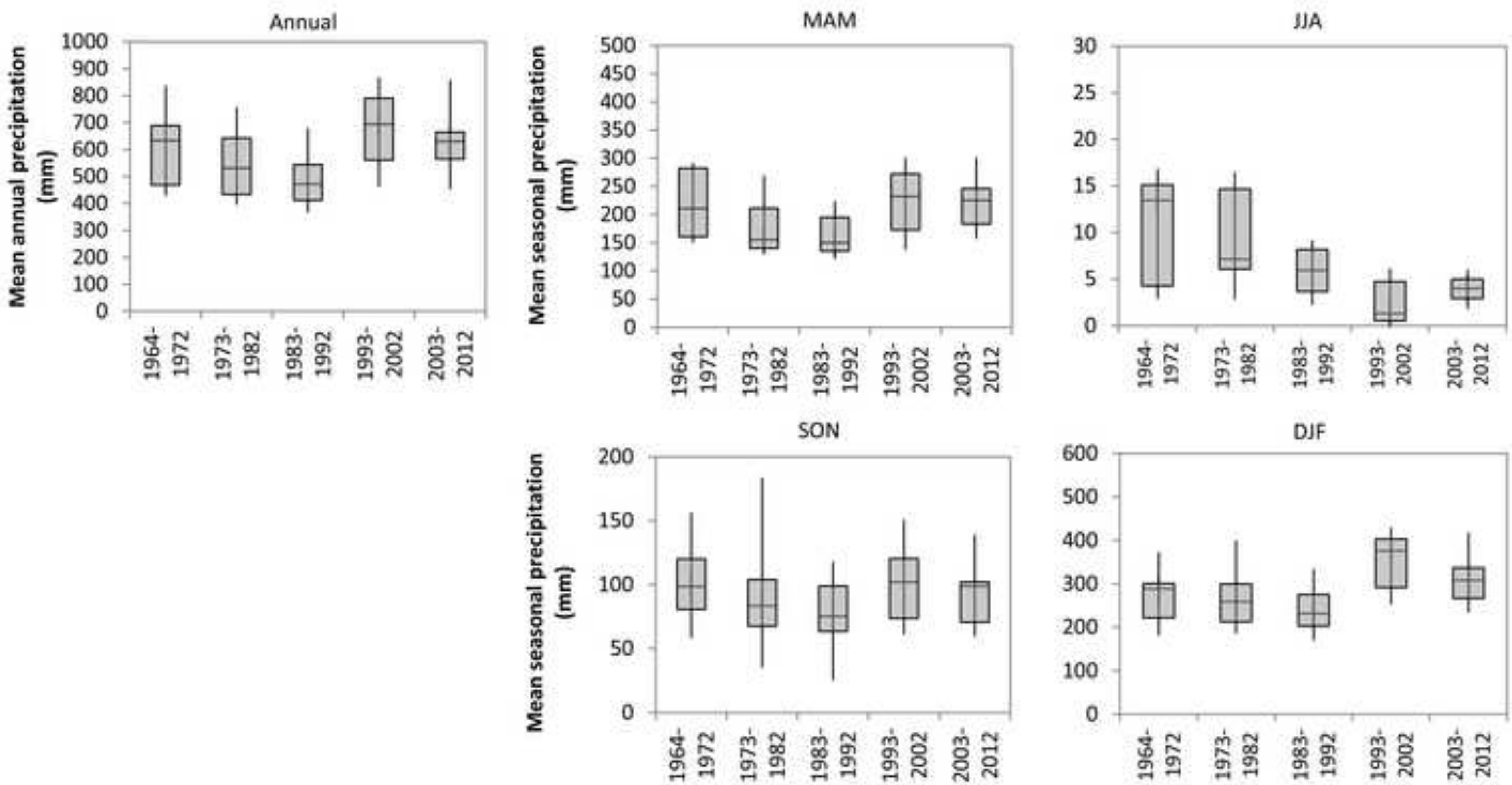

Figure10
Click here to download high resolution image

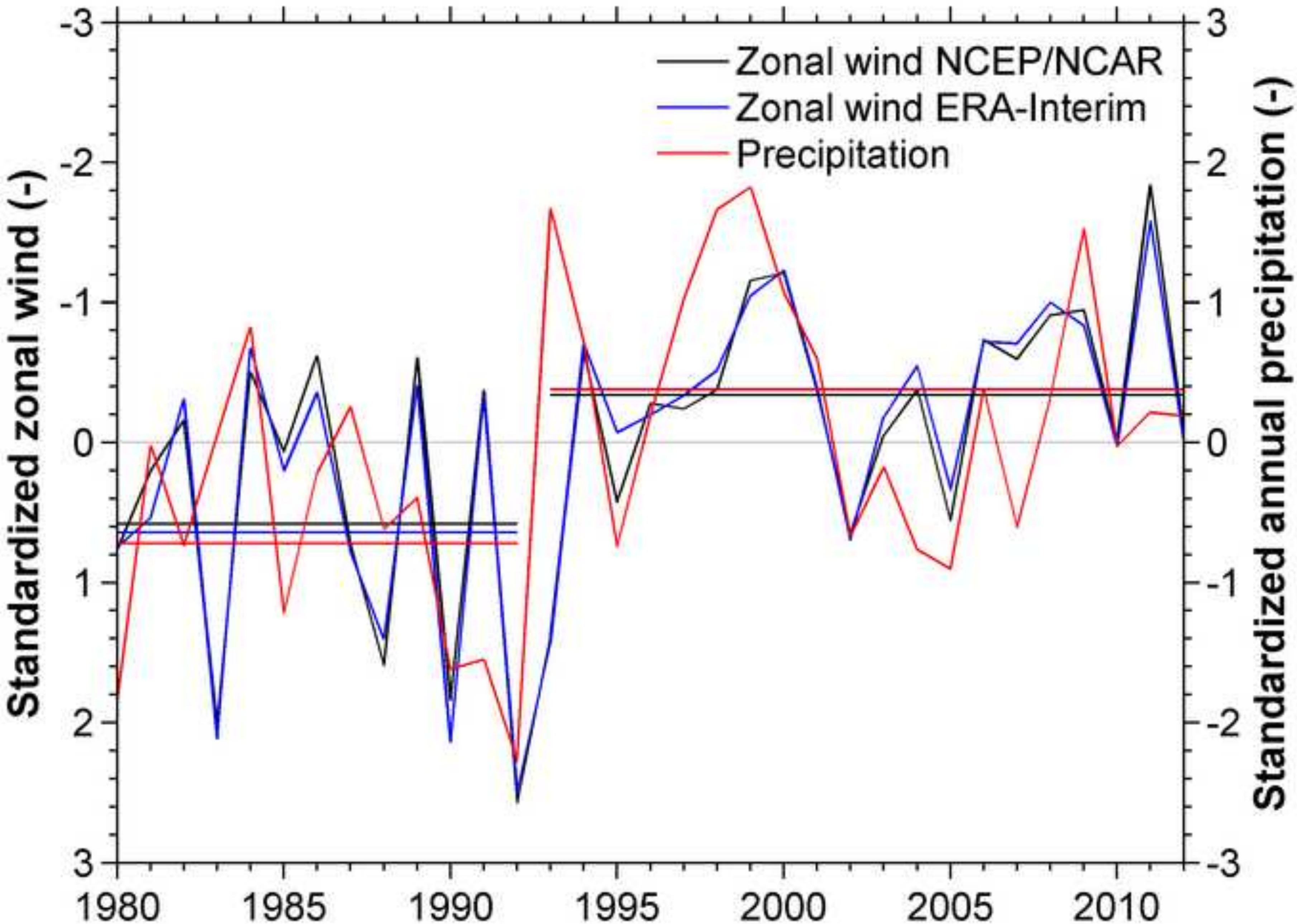

Figure11

Click here to download high resolution image

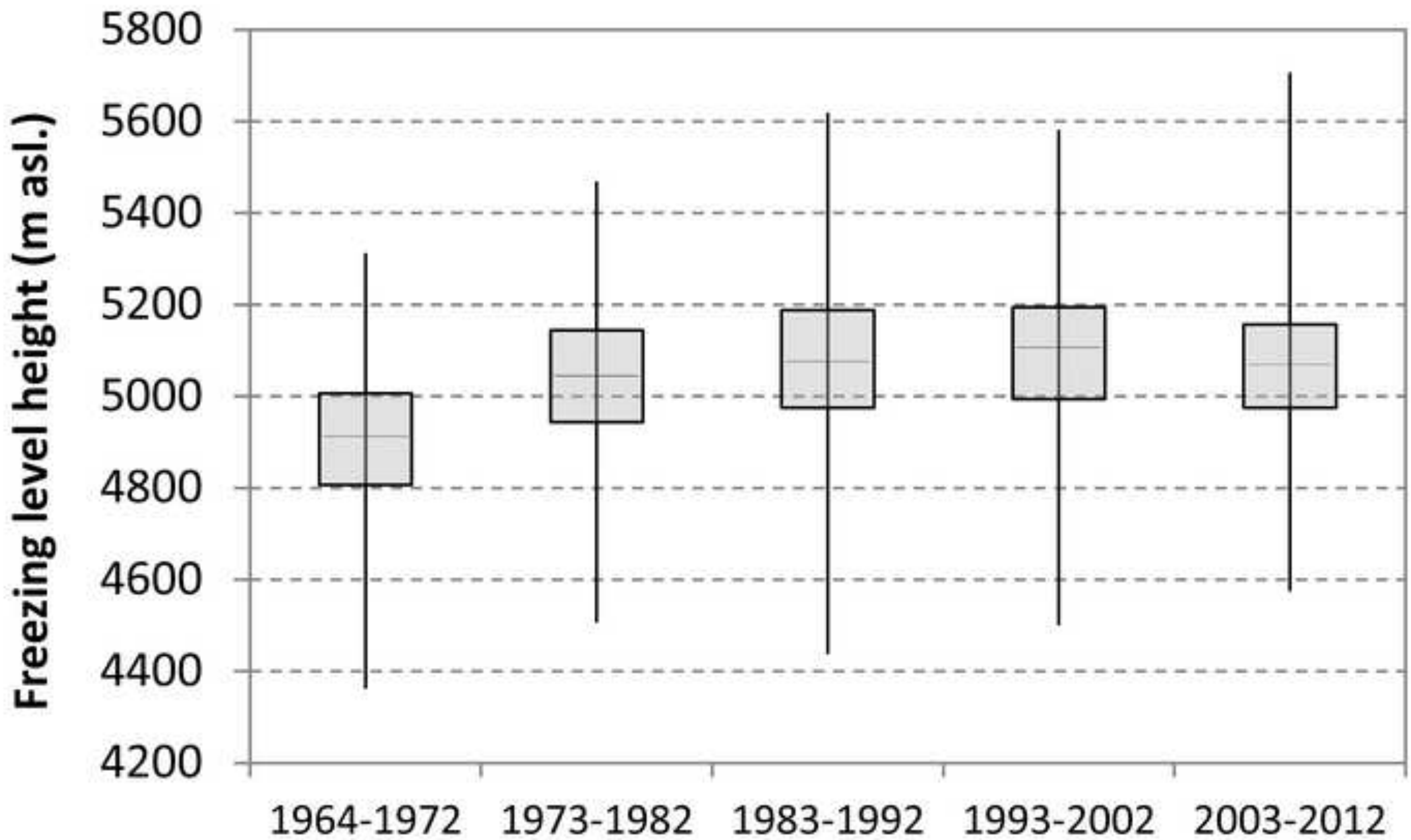

Figure12

Click here to download high resolution image

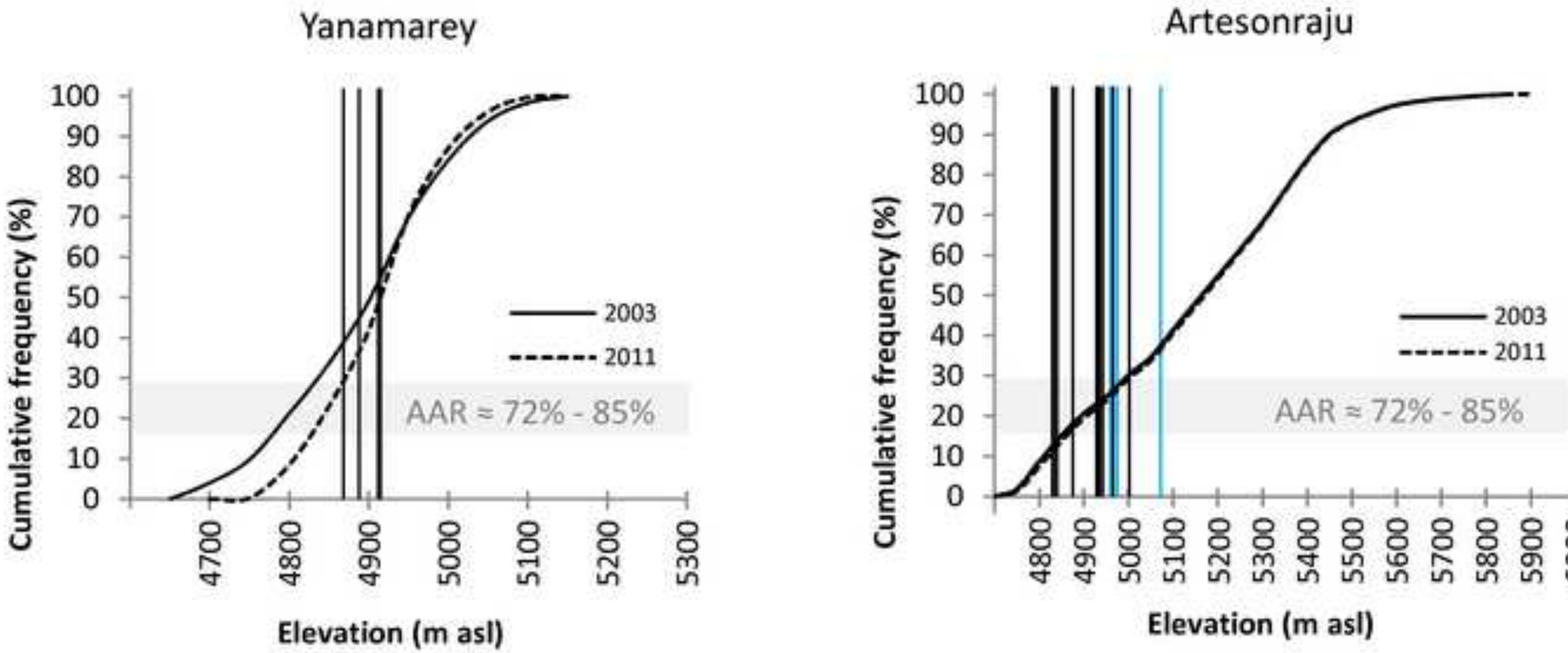

Table1

Station Name		Zone	Altitude	Variables	Period	Gaps (years missing)
Recuay	*	CB	3532	Tmax	1965-2010	1971/72, 1974-78, 2000/01, 2005/06
				Tmin	1966-2012	1970-72, 1974-78, 1980, 1986/87, 1991, 2005/06, 2011
Oyon		CB	3676	Tmax	1964-2012	1983-1986, 1997, 2004-07, 2011
				Tmin	1964-2012	1983-86, 1992-94, 2006/07, 2011
San Rafael		CB	3060	Tmax	1966-2012	1974-81, 1983-89, 1991-93
				Tmin	1966-2012	1974, 1983-89, 1991-94
Buena Vista	*	Coast	216	Tmax	1967-2012	1970, 2011
				Tmin	1967-2012	1970, 2011
Laredo		Coast	253	Tmax	1965-2002	1978/79, 1985-87, 1989
				Tmin	1965-2002	1978, 1985-87
Paramonga		Coast	120	Tmax	1971-2007	1972,1974,1978-84, 2004/05
				Tmin	1971-2007	1972, 1974, 1978-1984, 2004/05
Artesoncocha	*	CB >4000 masl	4838	Tmean	2002-2011	only 2004 and 2006 are complete
Andajes		CB	2725	P	1964-2012	11
Cachicadan		CB	2890	P	1964-2010	12
Cajatambo		CB	3325	P	1968-2012	23
Chacchan		CB	2285	P	1964-2012	9
Chiquian		CB	3382	P	1965-2012	29
Cotaparaco		CB	3170	P	1964-2009	13
Jacas Chico		CB	3673	P	1975-2012	11
Julcan		CB	3460	P	1965-2012	13
Mollepata		CB	2580	P	1964-2010	10
Ocros		CB	3179	P	1965-2012	7
Oyon		CB	3676	P	1968-2012	27
Paccho		CB	3110	P	1966-2010	7
Pampa libre		CB	1960	P	1976-2012	13
Parquin		CB	3590	P	1970-2009	10
Picoy		CB	3075	P	1982-2012	10
Pira		CB	3625	P	1965-2009	13
Recuay	*	CB	3444	P	1965-2010	19
Sihuas		CB	3375	P	1965-2012	29

Table2

Name	Spatial coverage	Pressure levels	Temporal coverage	Institution	Citation
NCEP/NCAR	2.5°	17	1948 to present	National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR)	Kalnay et al. (1996)
ERA-Interim	1.5°	37	1979 to present	European Centre for Medium-Range Weather Forecasts (ECMWF)	Dee et al. (2011)
ERA-40	2.5°	23	1957 to 2002	European Centre for Medium-Range Weather Forecasts (ECMWF)	Uppala et al. (2005)